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Space Exploration Initiative Fuels, Materials and Related Nuclear Propulsion Technologies Panel

Final Report

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FOREWORD

This report was prepared by members of the Fuels, Materials and Related Technologies Panel, with assistance from a number of industry observers as well as laboratory colleagues of the panel members. It represents a consensus view of the panel members. This report has not been subjected to a thorough review by DOE, NASA or DoD, and the opinions expressed herein should not be construed to represent the official position of these organizations, individually or jointly. There are no implications of funding decisions in the strategies presented here.

The authorship represents major contributors to the writing of the report. All panel members and observers (see list in Appendix A) made very substantial contributions to the contents of the report. Additional information provided by the concept focal points is also gratefully acknowledged.

This report was actually written in 1991 and is consistent with the charter and direction given to the panel, based upon the approved national program at that time. However, due to changes in national space policy and planning, some of the information has become dated. The final version of the report has incorporated some of these changes. However, a total update of the report is not planned at this time.

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EXECUTIVE SUMMARY

Nuclear propulsion has long been considered to be enabling for space missions to Mars and beyond. The recent renewed interest in space exploration has rekindled interest in developing this technology. Because of the anticipated problems with microgravity, galactic radiation, and isolation on humans in space, minimal transit time to Mars is a high priority. Nuclear propulsion has significant advantages over competing concepts in this regard.

The requirements of the nuclear propulsion systems have been derived from a large number of mission analyses. Nuclear Thermal Propulsion and Nuclear Electric Propulsion engine requirements were determined that could potentially meet the overall Mars mission requirements. All of them translated to significantly more severe operating conditions for the reactors than current technology would allow, and a major technology development would need to be undertaken to meet these requirements.

A Steering Committee comprised of Earl Wahlquist (DOE), Gary Bennett (NASA), and Roger Lenard (DoD) was established in 1990 to start assembling a technology development plan. One of their actions was to convene six panels comprised of experts from the various disciplines required for nuclear propulsion development and to task them to address the development issues and requirements in the various technology areas. Our panel, consisting of representatives from DOE, NASA and DoD laboratories, and assisted by industry observers, was asked to focus on the issues of fuels, materials and related technologies.

Nuclear Thermal Propulsion (NTP) is characterized by very high temperature exhaust gas (~ 3000 K), high specific impulses (Isp) and relatively short operating times (hours). Nuclear Electric Propulsion (NEP) systems have lower coolant temperatures (1500-2000 K), very high Isp values and considerably longer operating times (years). The NTP and NEP systems will need to demonstrate high reliability. The different operating conditions require different development paths for the components of the two systems, particularly fuels and materials. However, since minimizing cost will be a significant consideration, every attempt needs to be made to exploit commonality in development.

In June and July, 1990, workshops in NEP and NTP were conducted in which a set of 19 potential concepts were presented. Their technologies ranged from reasonable extrapolations of concepts developed earlier (NERVA derivative) to very speculative levels. The information content of the concepts was also very non-uniform. For the solid core reactor concepts, the fuels were characterized into the following geometric categories: prismatic elements, particle bed elements, cermets, and pin type elements. Some commonalities exist in the fuel forms such that development of six fuel forms can address the range of options provided. For non-fuel materials, there was little definition at the workshops and the existence of a large number of components necessitated the selection of a large number of potential candidates. A clear need was established to maintain close coordination and control of the materials R&D activities.

The technical problems of developing fuels and materials to meet the demanding operating requirements are very challenging. The principal issue is one of demonstrated survivability under the temperature and environmental conditions for the required lifetimes. Fabricability and retention of adequate mechanical strength over life are significant considerations. Tolerance of high radiation fluxes and fluences is also required. As a general conclusion, NTP development appears to be dominated by fuels (and associated coatings) development and NEP development appears to be dominated by development of fuel and materials for longer operating life and higher temperatures as well as features that reduce the overall NEP system mass. Based upon all the evidence examined, the panel believes that fuels and materials can be produced that can meet the requirements--at least at the low end of the acceptable temperature range. Significant development, testing, and evaluation will need to be undertaken, but no obvious insurmountable obstacles are foreseen. For improved performance engines, revolutionary advances in technology are required and advanced concepts need to be studied.

A thorough, technically defensible development program for fuels and materials for nuclear propulsion will take time and will require significant funding. A full matrix of options, including some associated work tasks, are provided so government planners will have a broad choice of concepts and technologies to select from and

pursue. The government, due to cost considerations, would be expected to narrow these choices and focus principally on the fuel forms and materials associated with the few concepts selected by the government for further development.

Estimates of costs of complex, long duration development programs are very hard to prepare and are subject to a set of inherent uncertainties imposed by the assumptions that are necessary to make such estimates. They are strong functions of the maturity of the concepts and technology, availability of funding, and development risks as well as other factors. Due to the uncertainties of which and how many concepts and technologies would be included in such a program, cost estimates are not included in this report. The schedule for development is assumed to match that proposed by the Nuclear Thermal Propulsion and Nuclear Electric Propulsion Technologies Panels.

For NTP fuels development, our recommendation is to take a balanced approach, with the additional features of carrying along a reference "established" NTP fuel form at the early stages of testing to maximize the chance of availability of one system at the desired TRL-6 date. If the more advanced NTP fuels prove to be feasible, a switch to the most promising of them can be made during the development period. NTP concept designs and test facility designs need to allow for this flexibility.

A balanced NTP fuels program should begin with early fabrication of uranium carbide and oxide particulate fuel that can be used to produce test samples of particle bed, prismatic graphite matrix, and prismatic metal matrix fuels. Early testing of these samples in hot hydrogen and in-reactor should provide important data for informed downselection of fuel concepts. This information, along with information from other technology development and systems design work, would lead to systems downselection and focussing of technology development work beginning about three years after the start of the program. The number of concepts that are carried through the detailed development will obviously depend upon the funding available. We would expect at least two fuels to be developed for testing in a fuel element test reactor at near prototypic conditions.

For NEP fuels development, the reference concept for all early missions is based on the SP-100 reactor and its derivatives. The fuels (UN clad in Nb-1ZrC or PWC-11)

are being developed as part of the SP-100 program as are the structural materials. While the SP-100 program funding has been smaller than desired, it remains the largest US space nuclear power program at the present time. Various options are being investigated for early flight tests of SP-100 based power systems. To supplement these ongoing efforts, the panel recommends incremental effort on fuels that lead to potentially higher performance reactor concepts (e.g. UN cermets). In addition, work on the particle bed and NERVA derivative fuels carried out for NTP needs to be followed to evaluate the potential use of these fuels in advanced NEP concepts.

For materials development, an evaluation of the probable requirements against available property information resulted in the identification of approximately one hundred candidate materials that can potentially be used in the nuclear propulsion systems. The panel was concerned that the materials development problems were not receiving adequate attention in the nuclear propulsion program planning. In order to ensure that the materials technology program receives the appropriate attention and retains the right focus, several specific management actions have been proposed. The technology development steps were grouped under alloys, composites, ceramics and coatings categories. Among the principal development issues was the need for immediate attention to: 1) identifying long lead-time refractory alloys to ensure availability of materials for testing, 2) initiation of planning and preparation for irradiation testing, and 3) initiation of planning and preparation for compatibility testing.

Success in this challenging endeavor will require the fullest utilization of the capabilities of the DOE laboratories, NASA centers, DoD laboratories, and universities and industrial organizations. The work will need to be carefully planned and continuously evaluated and focussed. On the basis of the interest and enthusiasm demonstrated at the panel discussions, we believe that the laboratories, universities and industries are up to the challenge.

I. INTRODUCTION

I.1 BACKGROUND

The use of nuclear energy for space propulsion has been under consideration from the early days of the development of nuclear power. Recent activity in space exploration has rekindled interest in nuclear power and propulsion for use in space missions. The interest in nuclear propulsion stems primarily from the promise of reduced trip times to Mars for manned missions relative to chemical propulsions. This is a major advantage because effects of radiation (cosmic and solar), microgravity and long-term isolation are anticipated to be significant problems for human astronavigation. Any reduction in trip times will result in enhanced mission performance and reduced risk. In a broader sense, nuclear power and propulsion systems will significantly enhance or enable a number of activities in space commerce, defense, and exploration areas.

Two classes of nuclear propulsion systems are under consideration. Nuclear Thermal Propulsion (NTP) systems are characterized by very high temperature exhaust gas from the reactors (~3000 K) and relatively short operating times (hours). Nuclear Electric Propulsion (NEP) systems are characterized by lower coolant temperatures (1500-2000 K) but considerably longer operating times (years). The NEP reactor systems bear a close relationship to surface power systems and could imply a shared development strategy in a number of areas. The NEP and NTP systems, however, involve different development paths and could involve different fuels and materials. The testing required to develop and qualify the fuels and materials are considerably different.

Since it was clear from earlier development activities that reactor fuels and materials and related technologies would be major technology drivers, a panel consisting of DOE, DoD, and NASA experts was established in December 1990 to address the principal issues and prepare development options for these technologies. The membership of the panel is shown in Appendix A; it represents a broad participation of the DOE laboratories in addition to the DoD and NASA representatives. In addition to the actual membership, the panel benefited greatly from the active

participation of a number of industry experts and the names of the principal participants are also included in the Appendix.

This panel (like the five companion panels that together addressed the Nuclear Propulsion development issues) was composed of volunteers. The modus operandi was to meet as a group approximately once a month starting January, 1991 to discuss the major issues. Considerable activity was undertaken by separate subgroups. The panel took full advantage of the large body of systematic preparations and evaluations of development plans for the Multi-megawatt space nuclear power program sponsored by DOE and SDIO a few years ago. In addition, the ongoing DOE-supported work at INEL and LANL in the fuels development area provided a large amount of information. These data where appropriate have been incorporated in this report.

I.2 CHARTER OF PANEL

The charter of the Panel, extracted from the letter by Earl Wahlquist[1] of DOE/NE, can be summarized by the following.

- Assess the nuclear fuels, materials, and reactor technologies for concepts proposed for SEI nuclear propulsion.
- Identify key issues with these technologies.
- Assess NTP/NEP reactor technology commonality.
- Identify critical testing needed for feasibility demonstration.
- Prepare technology development approaches and options.
- Prioritize recommended tasks (especially for near-term activities).

As initially conceived, the Panel was slated to have a broad reactor technology view. However, it became apparent that fuels and materials development required the greatest amount of attention since these are known to be the longest lead time, highest cost and greatest development risk items. A small amount of work has been done on the other reactor technologies and we suggest that these be expanded in the near future to produce a comprehensive reactor technology program plan.

Schedules are difficult to prepare because of the inherent uncertainties in the budgets. An attempt has been made in the report to lay out the tasks and ascribe elapsed time figures to these tasks in the fuels area, assuming adequate funding is

available to conduct these activities. However, it must be recognized that significant uncertainties exist in these estimates and that more detailed estimates will need to be performed when the program becomes better defined.

I.3 CONSTRAINTS

In the conduct of the panel work there were several significant constraints. Beyond the organizational and logistics constraints imposed by the volunteer efforts of a group of geographically separated people and the sheer number of panel members and observers involved are several technical ones. These are summarized below:

- A large number of development requirements for concepts were presented for both NTP and NEP. Because of the other constraints listed earlier, the task of categorizing the fuels and materials technological development requirements for these concepts was significant.
- The technology for the concepts had widely varying states of technology readiness levels.
- Reports on the concepts varied widely in the level of details.
- Our initial charter constrained us to considering only reactor materials. It was clear that this could lead to several significant materials issues (out of reactor) not receiving appropriate attention. Subsequently, we were given the charter of looking at all materials problems (proposed by other panels as well as ours).
- The initial work on fuels and materials was not aimed at downselection. The resources necessary to evaluate each type of fuel and material to gauge its applicability to space exploration missions were simply not available. The approach adopted was to categorize concepts by anticipated readiness dates.
- In preparing development options, alternative strategies need to be considered to account for the anticipated uncertainties in the budgets. Plans for required new facilities (and fallback positions if these plans are delayed) need to be developed.

I.4 ASSUMPTIONS

- A set of assumed engine requirements was derived by the NEP and NTP panels from the mission requirements that were developed by the Mission Analysis

Panel. These assumed requirements were used by the Fuels and Materials Panels.

- Instead of examining the range of possibilities of fuels and materials to meet the requirement, the Panel assumed the concepts presented at the NEP and NTP Workshops in 1990. This was necessary to keep the panel work bounded.
- The technology development plans presented at the Workshop started from the NEP SP-100 baseline and the NERVA based NTP system. The development needs presented at the Workshop represent the incremented requirements from the baseline states.
- It is assumed that the readers have access to the NEP/NTP workshop reports. No attempt has been made to present detailed descriptions of these concepts presented in the Workshop. A brief summary is presented in Section III for completeness.

I.5 INTERFACES WITH OTHER PANELS

Figure 1.1 presents the interaction scheme between the panels as we foresaw it when we started the work. The overall requirements for the NTP and NEP engines would be derived from the detailed mission analyses performed by the Mission Analysis Panel. This is an important step since the development options need to be keyed to specific missions (with associated perturbations there from). The NTP and NEP panels were then expected to translate these overall engine requirements into derived requirements for reactors that would drive the engines. These derived reactor requirements would form bases for the Fuels, Materials and Related Technologies Panel. Since the panel activities generally proceeded in parallel, this clean scheme did not work precisely as laid out. There were sufficient interactions between the various panels that the general requirements and their ranges were clear.

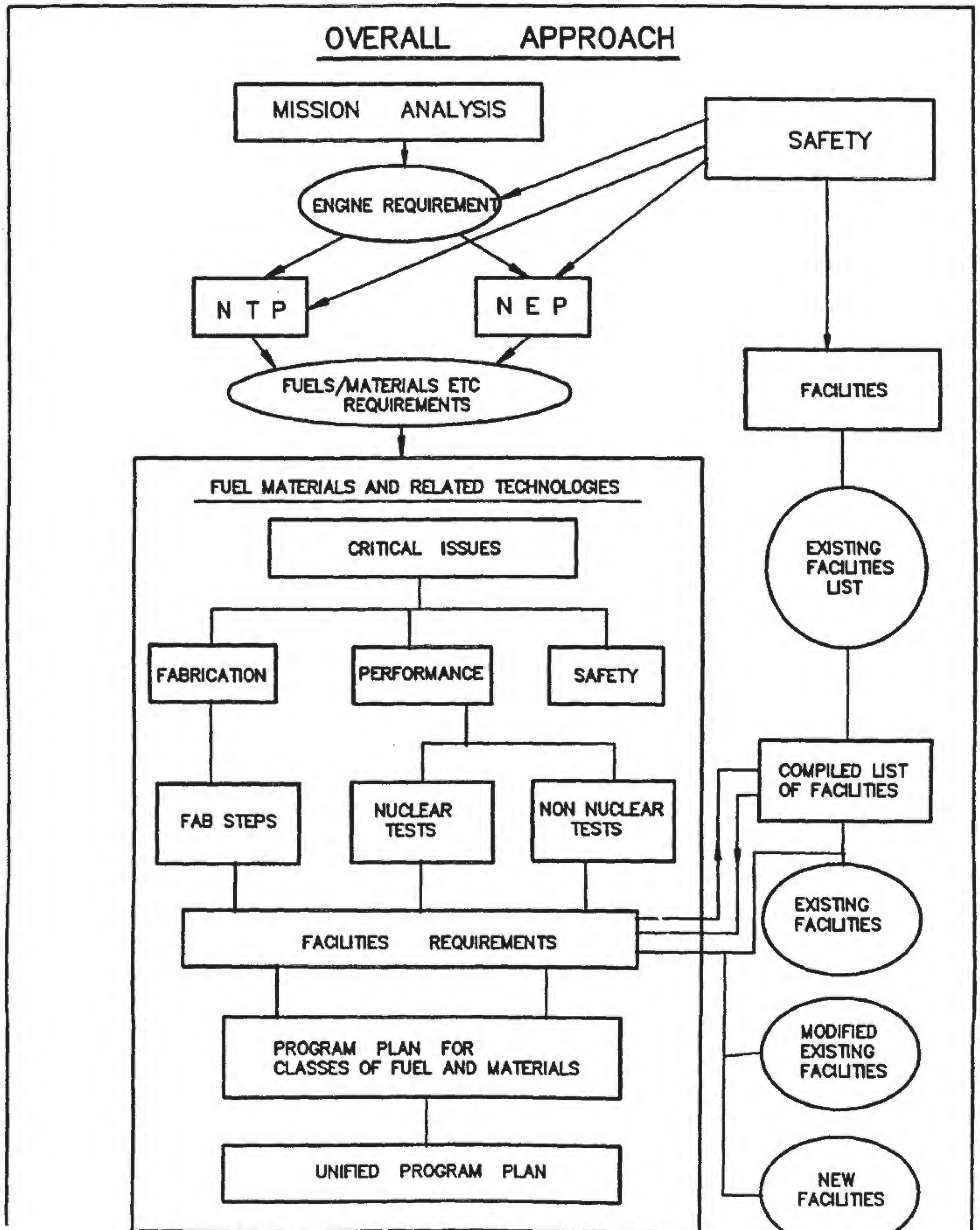


FIGURE 1.1 SCHEMATIC VIEW OF INTERFACES BETWEEN PANELS

I.6 DELIVERABLES

The panel had six major deliverables.

	Completion Date
• Draft report to Facilities Panel Stating Fuels/Material Development Requirement	4/15/91
• Interior Status Report to Steering Committee	4/23/91
• Draft final Report on Fuels Materials and Related Technologies	9/30/91
• Paper(s) at the OAI/SEI conference	9/03/91
• Paper at the Space Nuclear Power Symposium	1/15/92
• Final report	Late 1992

1.7 ORGANIZATION OF THE REPORT

The following sections of this final report are organized as follows. First, a discussion of the derived requirements on the fuels and materials for nuclear propulsion is presented. These form the starting point of the Panel's activity. Next, the concepts proposed to meet the NEP and NTP mission requirements are discussed in an overview sense. The intended operating conditions of the fuels and materials are extracted. A general discussion of fuels and materials development is next presented to lay out the principal issues. A section is devoted to the quantitative assessment of development issues as viewed by the concept proponents. Following this are two large sections that discuss fuels and materials development options. Next a brief overview of the technology development needs of other reactor technologies is presented. A section on materials requirements and needs for advanced concepts is included before a concluding summary section. References are listed at the end of each section.

Reference

1. Letter, E. Wahlquist to Distribution, December 1990.

II. REQUIREMENTS FOR FUELS AND MATERIALS DEVELOPMENT FOR NTP AND NEP

The requirements on the performance of fuels and materials are derived from the NTP and NEP panel assessments. In this section we present a summary of our understanding of the requirements as they evolved from the mission analysis.

Preliminary analyses have shown that specific impulse is an important parameter for Mars missions. Another important parameter used to measure performance in mission analyses is the initial mass in low earth orbit (IMLEO). Specific impulse has the largest impact on reducing the IMLEO, and although the higher the specific impulse, the lower is IMLEO, mission analyses indicate that a 925 s specific impulse is acceptable for a range of missions. From the specific impulse of 850 s for a NERVA engine with a chamber temperature of about 2500 K, a chamber temperature of approximately 2700 K is obtained by extrapolating the NERVA data to the specific impulse of 925 s. A 300 K temperature drop from the fuel to the chamber results in a 3000 K fuel temperature to achieve the 925 s specific impulse. A safety margin needs to be included to ensure that fuel temperature is maintained below the melting temperature. The margin is design dependent, but a 10% value has been assumed at this stage. Higher specific impulses can be achieved with fuel temperatures exceeding 3000 K.

The thrust-to-weight ratio is not important for ratios greater than 7 to 10 for Mars missions because the launch is assumed from a low-earth-orbit from Space Station Freedom. The ratio is not extremely important for such applications as orbital transfer vehicles (OTV); it could be slightly important for increasing reliability through the use of multiple engines for redundancy. Since mission analyses have not been performed yet to determine the effects of multiple engines on thrust-to-weight, the issue of the need for high thrust-to-weight ratios and hence high power densities is not clear for Mars type missions. Because of the large weights in hydrogen and hydrogen tankage, including an additional high thrust-to-weight engine might be insignificant. Although the thrust-to-weight ratio is not extremely important, it can

be increased by increasing the specific power density and consequently the fuel loading for a given neutron flux.

The total burn time for a Mars mission is expected to be at most 2 hours, and for margin, a total lifetime of 4.5 hours is assumed. This 4.5-hour lifetime also encompasses numerous start-ups and shut-downs for engine testing and propulsion maneuvers.

Fission product release needs to be considered at these high fuel temperatures (> 3000 K) during the fuel lifetime and for multiple transients. During NTP ground testing, fission product release would be minimized by means of an effluent treatment system. An effluent treatment system is needed, even for the best of fuels, since some fuel testing would be conducted to extremes well beyond normal expected operating conditions. For NTP space operations, fission product release would probably be controlled by the fuel itself, with fission product release being traded for fuel operating temperature and performance. For NEP systems the recirculating coolant could deposit released fission products at various points in its path, causing high local radiation doses. For both NTP and NEP systems, minimization of fission product release is prudent.

The assumed performance requirements for fuel development are summarized in Table II.1 for nuclear thermal propulsion along with the mission requirements that drive the fuel performance requirements.

The requirements are based on a 335 KN (75,000 lb) thrust engine for a Mars mission that was being developed for the ROVER/NERVA program. Since very little mission analysis was performed for a Mars mission, the 75,000 lb thrust engine was selected by trial and error and may not be optimal for a Mars mission. Other missions such as deep space probes, other non-space exploration missions, and civilian missions could be performed with much lower thrust engines. As an example, deep space probes could travel faster and carry heavier payloads than that from chemical propulsion. Although these missions do not absolutely require specific impulses as high as 925 seconds, the missions could be performed with lower performance, but

TABLE II.1

ASSUMED FUEL PERFORMANCE REQUIREMENTS FOR NUCLEAR THERMAL PROPULSION DERIVED FROM NASA ANALYSES	
> 925 s specific impulse	2700 K gas temperature in chamber 3000 K fuel temperature
< 10 thrust-to-weight ratio	Specific power more than 5 MW/ℓ Fuel loading greater than 700 Kg/m^3
4.5 h operating lifetime	Minimum fission product release Maintain dimensional stability
6 cycle lifetime	Capability to withstand transient cycling Minimum fission product release Maintain dimensional stability
Capability of use with alternate propellants	Provide indigenous coolant capability

higher specific impulses would still enhance the mission. The thrust-to-weight ratios required for these missions is on the order of 3 to 4 which is within the realm of the 5 MW/ℓ power density or less in the fuel to overcome gravitational drag.

For nuclear electric propulsion (NEP), the fuel operates at lower temperatures, but for longer times than those for NTP. Since the major application for NEP is cargo transport requiring low thrust and very high specific impulse, the total lifetime is anticipated to be of the order of 15 years of which the total operating lifetime is estimated to be 4 years. The NEP is expected to experience 15 transient cycles during the reactor's lifetime. For three missions per system, the average mission duration is 1-1/3 years. These long times impose stringent requirements for reliability.

Specific impulse does not demand higher fuel temperatures for NEP systems as is the case for NTP systems. However, the fuel temperatures are driven by the operating lifetime, the total lifetime, and the capability to retain fission products and fuel dimensional stability at the operating temperature.

The figure of merit for NEP systems is the specific mass ratio (α). A value of 10Kg/kW or less is necessary to meet the longer term missions. This ratio is driven to a major extent by the power density which in turn is affected by fuel loading and achievable fuel temperature. Part of the specific mass is determined by the power conditioning equipment and heat rejection components.

The assumed performance requirements for fuel development are summarized in Table II.2 for nuclear electric propulsion along with the mission requirements driving the fuel requirements.

TABLE II.2

ASSUMED FUEL PERFORMANCE REQUIREMENTS FOR NUCLEAR ELECTRIC PROPULSION DERIVED FROM NASA ANALYSES	
< 10 specific mass ratio	Specific power less than 0.5 MW/ℓ Fuel loading greater than 200 mg/cm^3
4 y operating lifetime	Minimum fission product release Maintain dimensional stability Fuel temperatures commensurate with lifetime and efficiency
> 15 cycle lifetime	Capability to withstand transient cycling Minimum fission product release Maintain dimensions stability

Table II.3 summarizes the top level derived requirements pertinent to fuels and materials development. While the table is generally self-explanatory, an observation is in order.

The upper range of NTP exit coolant temperature value of 3600 K was obtained from the Low Pressure Core concept (T2). In discussions with the concept focal point,[1] it was learned that this value was arrived at simply on the basis of the melting temperature of HfC. The panel does not believe that the NTP fuel concepts presented and discussed at the Workshop (and evolutionary extensions therefrom) justify exit coolant temperatures exceeding 3200 K as an upper limit. The panel has worked with the following.

TABLE II.3: REQUIREMENTS DERIVED FROM NTP AND NEP PANELS

PARAMETER	NTP	NEP
Exit Coolant Temperature (K)	3000 (2500 - 3600)*	- 1350 TE - 1350 - 1700 Rankine - 1700 - 1900 Brayton ~ > 2000 Thermionic**
Lifetime	- Maximum single burn: 1 hour - Total run time under 10 hours	7 year full power
Number of Cycles	6 per mission (maximum 23)	Multiple startups/shutdowns
Safety	Minimize fission product release (ALARA)	Withstand high burnups
Reliability***	TBD (as high as possible)	TBD
Power Level	1-2 GWt (75,000 lb. thrust)	5 MWe - 10 MWe
Anticipated Ramp Rates (startup)	TBD†	TBD†
Readiness Dates	- TRL 6 200/G - Lab scale 2700 K capability early	TRL 6 $\alpha < 50$ 1998 $\alpha < 50$ 2001 $\alpha <$ 2005

* A temperature of 3600 K was presented by one concept. It was based on the melting temperature of HfC and should be adjusted downward several hundred degrees K (design margin and fuel-to-gas temperature difference) to obtain an estimated coolant temperature.

** Emitter temperature.

- NTP exit coolant temperature values of 2500 K and above are acceptable.
- The higher the achievable temperature (consistent with other parameters--lifetime, safety, reliability) the better.

References

1. J. Ramsthaler, private communication, 1991.

III. OVERVIEW OF PROPOSED CONCEPTS

A number of nuclear electric propulsion (NEP) and nuclear thermal propulsion (NTP) concepts were presented at the workshops held at JPL on June 19-22, 1990 and at LeRC on July 10-12, 1990. These concepts were summarized at a feedback meeting in Houston, TX on November 15, 1990. The NEP concepts are summarized in presentation material presented at the latter meeting by John Barnett, NEP Workshop Chairman. The NTP concept presentation material is compiled in a loose-leaf binder that was distributed to the participants. These compilations were also presented at the 8th Symposium on Space Nuclear Power Systems, Albuquerque, NM, January 6-10, 1991 and published in those proceedings (Refs. 1 and 2).

We assigned an alpha-numeric designation to each of the concepts to facilitate identification. The first character of the designator is E or T depending on whether the concept is for NEP or NTP respectively. In the case of the NEP concepts, the sequential numbers following E are assigned in the same order as the concepts are presented in Ref. 1. This ordering is grouped by fuel material. We used the same fuel grouping rationale to order the NTP concepts and assigned sequential numbers accordingly. An index of the concepts and their designations is given in Table III-1. These designators are used to identify the concepts throughout this Panel report.

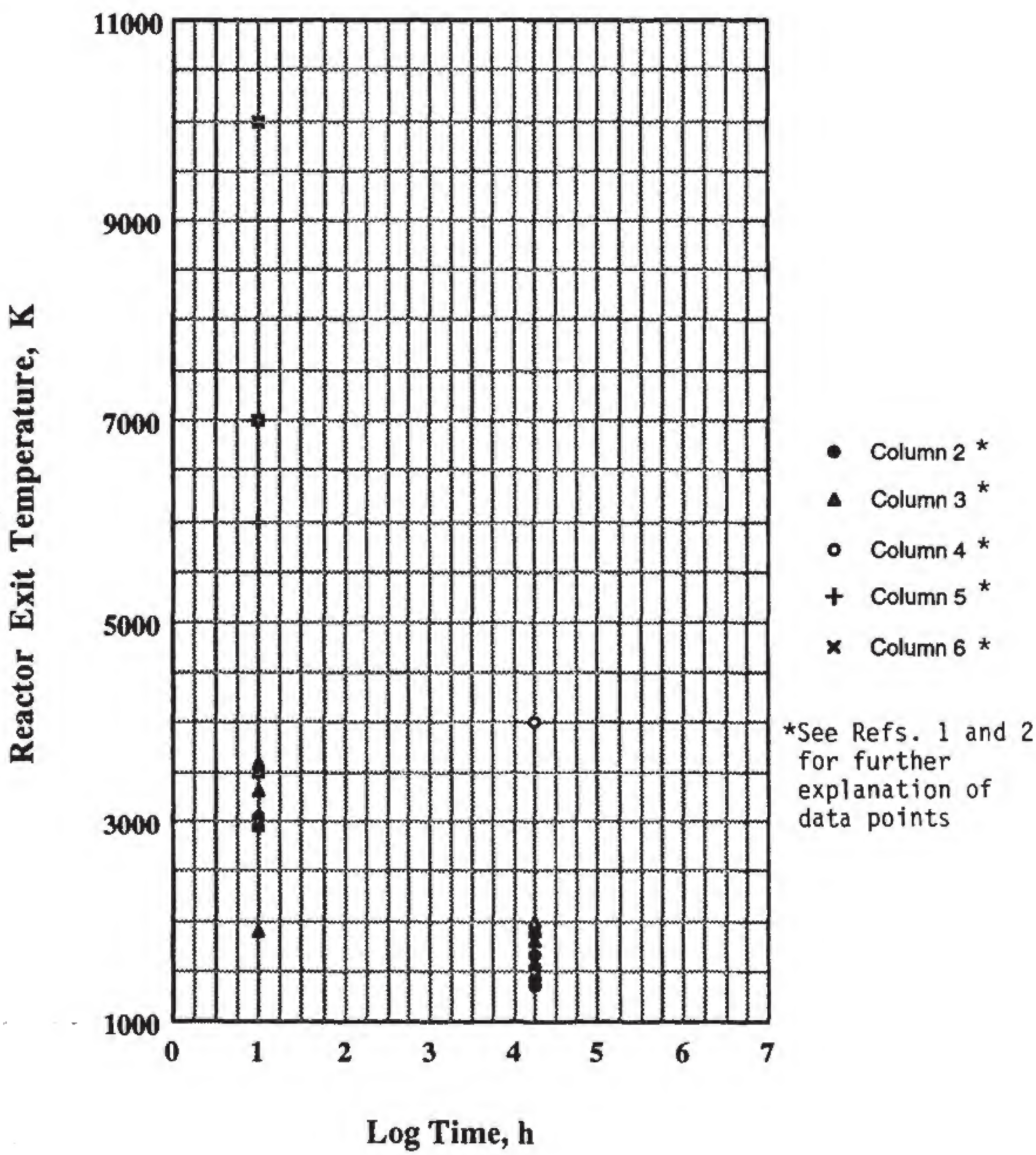
For completeness, we include below a description of each of the concepts. These descriptions are taken from Refs. 1 and 2. Figure 3-1 shows the temperature-time requirements for each of the concepts. We used the reactor exit temperature for each concept as these data were generally available and peak fuel temperature data were not. The NEP and NTP concepts are plotted at two characteristic time values, but their range of quoted temperatures is very large. The descriptions of the concepts are very brief and intended to be a factual summary of the focal point's presentation with no evaluations. The reader is referred to the original compilations (Refs. 1 and 2) for details. For ease of reference, the original papers are listed in the following paragraphs--however all the papers are identified in Refs. 1 and 2.

TABLE III-1

CONCEPT DESIGNATIONS, PROPOSING ORGANIZATION, AND CONCEPT FOCAL POINTS

Designator	Organization	Focal Point
	NEP	
E1 — SP100 Scaleup	GE	P. Pluta
E2 — 10 MWe Rankine	LLNL	C. Walter
E3 — Potassium Rankine	Rocketdyne	J. Mills
E4 — RMBLR	PNL	B. Johnson
E5 — ENABLER	Westinghouse	B. Pierce
E6 — NEPTUNE	Ohio State University	P. Turchi
E7 — Particle Bed	BNL	J. Powell
E8 — Pellet Bed	University of New Mexico	M. El-Genk
E9 — In-core Thermionic	GA	T. Van Hagan
E10 — TORCHLITE	PNL	B. Reid
E11 — Vapor Core	University of Florida	N. Diaz
	NTP	
T1 — ENABLER	Westinghouse	B. Pierce
T2 — Low Pressure Core	INEL	J. Ramsthaler
T3 — DUMBO	LANL	W. Kirk
T4 — Particle Bed	BNL	H. Ludewig
T5 — Pellet Bed	University of New Mexico	M. El-Genk
T6 — NIMF	Martin Marietta	R. Zubrin
T7 — Hybrid	PNL	B. Reid
T8 — Wire Core	Rocketdyne	R. Harty
T9 — Cermet	GE	G. Kruger
T10 — Foil	SNL	S. Wright
T11 — LARS	BNL	H. Ludewig
T12 — Droplet Core	University of Florida	N. Diaz
T13 — Gas Core	Sverdrup	R. Ragsdale
T14 — Vapor Core	University of Florida	N. Diaz
T15 — Light Bulb	United Technologies Research Center	T. Latham

Figure 3-1 Temperature/Time Conditions for Proposed NEP and NTP Concepts.



III.1 NUCLEAR ELECTRIC PROPULSION (NEP) CONCEPTS[3]

E1 - SP-100 Scale-up

The SP-100 reactor is the most advanced in the U.S. space nuclear reactor program. This reactor technology, designed for a reference power level of 2.4 MWth, can be scaled up to the power level appropriate for a piloted Mars mission (Darooka, et al, 1990). The SP-100 reactor is characterized by a fast neutron energy spectrum with UN pin-type fuel and niobium alloy structure . The primary coolant is lithium, with a reactor outlet temperature of 1375 K. Ex-core thermoelectric power conversion is employed to produce 100 kWe. The reactor is compatible with dynamic or static power conversion. With potassium Rankine energy conversion, the power system specific mass is estimated to be 7 kg/kWe at 10 MWe. The reactor is designed for intact reentry and impact, and has redundant systems for shutdown and for removal of reactor decay heat. The scale-up of SP-100 technology to power levels as high as 200 MWth (40 MWe) has been studied: no breakthroughs or new technologies beyond the current SP-100 program are required.

E2 - 10 MWe Rankine

This concept uses a fast energy spectrum reactor with UN fuel pins interspersed with cooling channels (Walter 1990). Structural material is tungsten rhenium. The primary coolant is lithium, with a reactor outlet temperature of 1650 K. The closed Rankine power conversion uses potassium as the working fluid. Waste heat is radiated from a flat, manifolded, heat pipe radiator. The specific mass of the system is estimated to be 7 kg/kWe at 10 MWe. Reactor control is provided independently by sliding side reflectors and by active control of the inventory of the lithium-6 in the control channels. The concept, first published 20 years ago, takes advantage of SP-100 fuel technology, and incorporates materials that are inherently compatible at high temperature (Li, W-Re, UN). Substantial development of the required fuel and materials has been done since the concept was first developed.

E3 - Potassium Rankine

In this concept, a UN-W/25 Re cermet fuel reactor is cooled with lithium (Mills 1990). A potassium Rankine cycle converts the heat to electricity. The reactor outlet

temperature is 1550 K. Carbon-carbon heat pipes are used for primary thermal rejection. The system specific mass is estimated to be 3 kg/kWe at 10 MWe. Safety features include redundant coolant loops, and both rods and reflectors for shutdown. Several of the required components and materials for this concept have been developed. Cermet fuel offers improved performance and safety margins over pin type fuel because its properties include high strength and thermal conductivity, and low thermal expansion. Fabrication of the cermet fuel requires additional development, as well as characterization of fuel behavior at temperature with up to 25% burnup.

E4 - RMBLR

The RMBLR concept employs a fast energy spectrum, UN/molybdenum alloy cermet fuel reactor cooled by boiling potassium (Johnson 1990). A direct Rankine cycle is used for energy conversion. The fuel is fabricated in the form of blocks with coolant channels. Potassium flows through the reactor in an inward radial flow to reduce thermal stress, leaving the reactor as vapor at a temperature of 1440 K. With a bubble membrane radiator the specific mass at 20 MWe is estimated to be 1-2 kg/kWe. The radial coolant inflow results in a reduced reactor vessel operating temperature, which has potential benefits in operations and safety. This is a very lightweight, advanced concept, and substantial development is required.

E5 - ENABLER

ENABLER incorporates a NERVA derivative, thermal energy spectrum, gas cooled reactor, with a closed Brayton cycle (Farbman and Pierce 1990). The fuel is in the form of a UC bead, of diameter on the order of 0.5 mm, coated with ZrC. The reactor is cooled by a mixture of helium and xenon, which exits the reactor at 1920 K. Specific mass of the system is estimated to be about 3 kg/kWe at 10 MWe. An advantage of this concept is that feasibility of the reactor has been generally demonstrated in the NERVA tests of the 1960s, which led to reactors approaching space qualification. The use of inert coolant eliminates hydrogen corrosion. Fuel testing of the ZrC-coated beads at up to 25% burnup is required. Graphite growth characterization data are also required.

E6 - NEPTUNE

The NEPTUNE concept provides high system specific power (unstated) by coupling an advanced high-temperature gas-cooled reactor (based on NERVA) with a non-equilibrium magnetohydrodynamic (MHD) generator in order to produce electric power directly matched to a low impedance thruster, such as an MPD thruster (Turchi 1990). The MHD generator output can be used by some electric engines without further conditioning. The reactor might employ NERVA-style UC_2/C fuel and hydrogen coolant, with a reactor outlet of about 1900 K. Substantial development is required.

E7 - Particle Bed

The reactor in this concept is a gas-cooled particle-bed design (Powell and Brandes 1990). Both thermal and fast energy spectrum variants are possible. The fuel consists of particles of UC_2 encased in porous pyrolitic graphite and SiC (or ZrC); the particle diameter is about 0.5 mm. The coolant is a mixture of helium and xenon, with a reactor outlet temperature in the range of 1100 to 2000 K. A closed Brayton cycle is used for power conversion. For this system, a specific mass of about 4 kg/kWe at 10 MWe is estimated. Control rods are used in the thermal version, and control drums in the fast version. Potential for low specific mass may be realized at high reactor outlet temperatures because of the enhanced heat transfer area of the fuel particles and use of a direct Brayton cycle. The thermo-hydraulic behavior in the particle bed fuel elements is a significant issue and has been analyzed in some detail. Commercially available fuel particles are suitable for operation up to 1700 K. Several components of the power system require development at the higher temperatures.

E8 - Pellet Bed

The Pellet Bed concept uses a hydrogen cooled, fast energy spectrum pellet-bed core with a potassium Rankine cycle for energy conversion (El-Genk 1990). The fuel consists of ZrC-coated graphite pellets. The pellets are spherical, with a diameter of about 1.0 cm. UC-ZrC particles are embedded in the graphite. The large heat transfer area of the pellets allows high reactor outlet temperatures. The primary coolant (hydrogen) leaves the reactor at 1800 K. Estimated specific mass of the system is about 6 kg/kWe at 10 MWe. In a variant of this system, energy conversion is accomplished with a closed helium Brayton cycle; in this case, the helium directly

cools the reactor. This variant is expected to provide lower specific mass. Division of the reactor into three sections is intended to eliminate single point reactor failure. On-orbit refueling may be possible.

E9 - In-core Thermionic

In this concept, a fast energy spectrum reactor with thermionic fuel elements is cooled by sodium or possibly NaK (Van Hagan 1990). The UO_2 fuel is in pellet form contained by the thermionic emitter. The system specific mass is estimated to be about 4 kg/kWe at 6.5 MWe. The close packed hexagonal array of thermionic fuel elements offers structural integrity, and the design can accommodate a loss of coolant accident without melting.

The single coolant loop operates at the rejection temperature level. The thermionic converter has been characterized at emitter temperatures between 1700 and 2000 K, and collector temperatures between 800 and 1200 K.

E10 - TORCHLITE

The TORCHLITE concept uses thermionic power conversion (Reid and Webb 1990). UO_2 rods are used as fuel, with pumped liquid metal or heat pipes for primary cooling. Specific mass of the system is estimated to be about 5 kg/kWe at 5 MWe and is mass competitive with other concepts up to about 6 MWe. There are two reactor variants. Substantial development is required. The pumped liquid metal fast reactor variant requires further study of coolant circulation during startup and shutdown. The beryllium - moderated heat pipe variant requires further heat pipe development, heat pipe thermal coupling in the core, and development of stabilized ZrH. (Operating temperatures not given.)

E11 - Vapor Core

In this concept the fuel exists in a vapor state in the core of the reactor, intimately mixed with the working fluid, and contained in a closed Rankine cycle (Diaz 1990). The proposed fuel is UF_4 vapor, with an alkali metal fluoride used as the working fluid. The reactor outlet temperature is about 4000 K, with power conversion accomplished by a magnetohydrodynamic (MHD) system. Specific mass of the system is estimated at 3 to 8 kg/kWe for operation in a burst mode between 10 and 70 MWe. Nuclear design, fuel chemistry, and nuclear-MHD plasma physics

are currently being studied. The key developmental requirements are a gas core reactor feasibility demonstration; characterization of the gas core non-equilibrium plasma; MHD channel design; and coupled gas core reactor-MHD channel feasibility demonstration. Again, substantial development is required.

III.2 NUCLEAR THERMAL PROPULSION (NTP) CONCEPTS[4]

T1 - ENABLER

The ENABLER concept (Pierce, 1990) is an updated version of the NERVA baseline technology. The hexagonal fuel elements have 19 circular coolant channels through which the hydrogen propellant passes and is heated. The baseline fuel is uranium carbide-carbon composite. This fuel may permit a nozzle inlet temperature of about 2700 K resulting in a specific impulse I_{sp} of about 9.1 km/s. As binary and ternary carbide fuels are developed, it is projected that nozzle inlet temperatures and specific impulses can be increased to 3100 and 3300 K, and 10.0 and 10.6 km/s, respectively.

T2 - Low Pressure Core

The Low Pressure Core concept (Ramsthaler, 1990) features a spherical core with radial outflow of hydrogen to maximize the high temperature heat transfer area. The concept includes two variant fuel configurations: particles or platelets of UC-ZrC. The system is proposed to operate on tank pressure, thus eliminating turbopumps. Reactivity in the core is controlled by the amount of hydrogen in the core, thereby eliminating control drums. Operation at a low pressure of 0.1 MPa is projected to result in heat transfer augmentation as a result of hydrogen dissociation-recombination effects, yielding up to 30% higher specific impulse, 11.8 km/s, for an exit gas temperature of 3600 K. The relatively small size (49 kN thrust) makes clustering necessary, permits redundancy on a variety of missions, and possibly reduces testing costs. Because of the low pressure operation, ground testing system requirements will be different and perhaps more costly than for high pressure concepts.

T3 - DUMBO

DUMBO is a "folded flow" concept (Kirk, 1990) utilizing UC-ZrC fuel washers and "spiders" in a radial flow configuration. It represents an advanced concept that

evolved from the NERVA program as a means of achieving improved heat transfer within the core. Operating temperatures were not stipulated. The fuel data provided may allow an exit temperature gas temperature of 2950 K.

T4 - Particle Bed

The Particle Bed concept (Ludewig, 1990) uses fuel particles that are 0.5 to 0.7 mm diameter. The fuel particle is formed with an inner fuel core of UC_2/ZrC, coated with layers of porous carbon, pyrolytic carbon, and ZrC. Hydrogen enters the core through axial passages in the moderator block, and passes radially through the cold frit, the fuel particle bed, and the hot frit. Reactor gas exit temperatures are projected to be in the range of 3000-3500 K.

T5 - Pellet Bed

The Pellet Bed concept (El-Genk, 1990) is made up of many microspheres or UC-TaC or UC-NbC fuel, encapsulated in carbon and TaC or NbC coating. The microspheres are embedded in a spherical graphite matrix, coated with ZrC. Maximum fuel temperatures of about 3100 K are projected for an exit hydrogen temperature of 3000 K. Thermal-hydraulic studies are required to evaluate the concept potential.

T6 - NIMF

The unique characteristic of the Nuclear Indigenous Martian Fuel (NIMF) concept (Zubrin, 1990) is the use of carbon dioxide from the Mars atmosphere as the reactor coolant and propellent. NIMF would provide the propulsion means for traveling to various locations on the surface and for return to the orbiter (or return directly to Earth). NIMF requires fuel materials that can withstand deterioration in hot (>2200 K) CO_2. Candidate materials are suggested to be ThO_2, ZrO_2, BeO, $UO_2/Th\ O_2$ at temperatures as high as 2800 K. At lower temperatures (<1900 K) NERVA fuel (UC_2) technology may be applicable.

T7 - Hybrid

The Hybrid concept (Reid, 1990) utilizes a NERVA system for high-thrust propulsion and a Brayton cycle NEP system with MPD thrusters to augment thrust during transit to and from Mars. The system could offer reduced trip times for the manned Mars mission. No performance data were provided.

T8 - Wire Core

The Wire Core concept (Horty, 1990) was conceived in the 1960s. It utilizes a unique swaged and drawn fuel wire of 0.9 mm diameter. Starting materials for the wiremaking process are 0.2 mm diam tungsten wire, vapor deposited tungsten and 0.1 mm UN particles. Reactor exit hydrogen temperature is 3030 K.

T9 - Cermet

The Cermet concept (Kruger, 1990) is based on the earlier (1960s) "710" program and the alternative to NERVA nuclear rocket program which included significant design, fabrication, and testing accomplishments. The UO_2W cermet fuel is believed to excel in fuel and fission product retention capability. A peak fuel temperature of 2730 K results in a reactor hydrogen exit temperature of 2500 K, that provides a specific impulse of 8.2 km/s at a thrust level of 450 kN. There are indications that higher temperatures are possible, but this needs to be demonstrated.

T10 - Foil

The Foil reactor concept (Wright, 1990) is a spinoff from the nuclear-pumped-laser program. The concept involves applying very thin foils of U-UO_2 to a thin foil (1-2 mm) of high-temperature substrate material. The fission fragments directly heat the flowing hydrogen. Thus, it is possible to obtain hydrogen temperatures greater than the maximum material temperature in the reactor. Fission fragments heat the gas to as much as 1000 K greater than the substrate. Propellant exit temperature is estimated to be 3400 K, for an I_{sp} of 9.7 km/s. The projected system has high thrust and is large. The reactor core requires large reflectors and is itself generally larger because of the dilute fissile loading.

T11 - LARS

In the Liquid Annular Reactor System (LARS), a portion of the UC_2 fuel operates substantially above its melting point at a temperature of 6000 K (Ludewig, 1990). A stable configuration is provided by rotation of seven drums which contain inner layers of molten fuel. At the drum the fuel is solid. Hydrogen flows axially through the drum. Hydrogen becomes dissociated, leading to specific impulse in the range of 15.7 to 19.6 km/s as recombination occurs.

T12 - Droplet Core

The Droplet Core concept (Diaz, 1990) relies on recirculation of liquid uranium droplets. The droplets are formed by a hydrogen atomizer and stand-off from the vessel wall because of radially inward hydrogen flow. At temperatures of 5000 to 7000 K reached by the hydrogen, it dissociates and recombines, resulting in specific impulses in the range of 15.7 to 19.6 km/s. Fission fragment heating of the hydrogen is also projected, with 50 percent of the fission fragment energy entering the hot gas.

T13 - Gas Core

In the Gas Core concept (Ragsdale, 1990) there is direct contact between uranium plasma and the hydrogen flow. A seed material is added to the hydrogen to help absorb the radiant energy and to protect the walls of the cavity. A flow field is set up to maintain a stagnation region in the center of the sphere to prevent excessive loss of fissionable material through the nozzle. The high uranium plasma temperature of 10,000 K results in the high specific impulse of 51 km/s.

T14 - Vapor Core

The Vapor Core concept (Diaz, 1990) is a uranium tetrafluoride (UF_4) fueled reactor. The vapor fuel is contained in canister assemblies and does not circulate. Hydrogen propellant flows in tubes within the canisters. Containment of the vapor can be accomplished with a number of materials. The high fuel vapor temperatures projected (4000-5000 K) result in hydrogen temperatures of about 3500 K and a specific impulse of 12.5 km/s.

T15 - Light Bulb

The Light Bulb concept (Latham, 1990) also includes containment of the nuclear fuel with radiant heat flux passing through internally-cooled fused-silica transparent walls to a seeded hydrogen propellant. A reference design contains seven modules that fit in the shuttle bay. A plasma temperature of 7200 K results in an I_{sp} of about 18.3 km/s, which can be traded off against trip time or IMLEO.

III.3 IDENTIFICATION OF DEVELOPMENT ISSUES

As an aid for scoping the technology development program that would be associated with each of the NEP and NTP concepts, taken singly and all together, we

compiled the available information as shown in Fig. 3-1 and in Tables III-2 and III-3. these tables also include preliminary assessments of technology readiness levels.

References

1. Barnett, J. W., NEP Technologies: Overview of the NASA/DOE/DOD NEP Workshop, Proceedings 8th Symposium on Space Nuclear Power Systems, American Institute of Physics CONF 910116, Part 2, p. 511, January 1991.

2. Clark, J. S., A Comparison of NTP Concepts: Results of a Workshop, Proceedings 8th Symposium on Space Nuclear Power Systems, American Institute of Physics CONF 910116, Part 2, p. 740, January 1991.

3. All of the referenced papers were handed out at the workshop. Copies may be obtained directly from the authors.

4. All of the referenced papers are included in the Proceedings of the "Nuclear Thermal Propulsion" Workshop (July 1990) NASA Conference Publication 10079, published in 1991.

TABLE III-2 NUCLEAR THERMAL PROPULSION SUMMARY WORKSHEET

REACTOR	FUEL	STRUCTURAL MATERIALS			TEMPERATURE (K)		**Q1	**Q2	**Q3	**Q4	READY LEVEL	CRITICAL TECHNOLOGY ISSUES
		Cladding	Coating	Matrix	Fuel	Exhaust						
NERVA/ROVER	UC2 bead		ZrC	Graphite		2500	Yes	Yes	Yes	Yes	8.0	H2 compatibility, mid-band corrosion, cracking
	(U,Zr)C-C composite		ZrC	Graphite		2700	Yes	Yes	Some	Yes	5.0	H2 compatibility, cracking eutectic formation
	(U,Zr)C solid solution					3100	Maybe	Yes	Few	Probably	4.5	Melting point, H2 compatibility, fabricability and homogeneity of rods
	(U,Zr,Nb)C solid solution					3300	No	???	No	???	1.0	Melting point, stability, fabricability, H2 compatibility
Low Pressure Core-Particle Bed Reactor*	(U,Zr)C beads or (U,Zr)C wafers	ZrC foam & Zr frit	ZrC			3200	No No	Yes Probably	Few Few	Probably Probably	1.0 1.0	Melting point, compatibility with mono-atomic H, coating volatility, fabrication of wafers
	(U,H)C beads or (U,H)C wafers	ZrC foam &ZrC frit	ZrC			3100	No No	??? ???	No No	??? ???	0.5 0.5	Ditto plus unknown properties, melting point & stability of (U,H)C
Particle Bed Reactor	(U,Zr)C bead	Coated graphite	ZrC/NbC		3200	3000	No	Probably	Few	Probably	2.0	Melting point of fuel, stability of high surface area particle coatings
	(U,Zr,Nb)C bead solid solution	Coated graphite	ZrC/NbC		3300	3100	No	???	No	???	1.0	Ditto plus unknown properties of (U,Zr,Nb)C
Cermet Fuel Reactor	UO2	W-Re		W	2728		Yes	Yes	Yes	Yes	4.5	UO2 stability, gas retention in cermet, W-Re fabrication
NIMF: Nerva Type Core*	UC2,UO2/ ThO2,?		BeO,SiC, NbC	???	>2200		No	No	???	Probably	1.0	Fuel and coating compatibility with CO2
Wire Core Reactor	UN particles	W		W		3030	Yes	Probably	Some	Maybe	2.0	UN/W compatibility, W-wire fabrication, UN stability
Advanced Dumbo	(U,Zr)C washers	W or Mo					No	Yes	No	Maybe	1.0	Fuel fabrication, fuel stability and melting point
Pellet Bed Reactor	(U,Nb)C or (U,Ta)C beads		TaC or NbC & ZrC	Graphite	3100	3000	No	Maybe	No	Probably	1.0	Unknown fuel & cladding properties fabricability
Foil Reactor	UO2 or (U,Zr)C		BeO		2000-3000	2700-4000	Yes	Yes	Most	Probably	1.5	Stability of fuel coatings on substrate, H2 compatibility and kinetics

* Hydrogen is the propellant for all fuels listed with the following exceptions: Low Pressure Core Particle Bed Reactor: H2+H; NIMF: CO2

** Question 1: Have fuels and materials been developed?
Question 2: Can fuels and materials be developed?
Question 3: Are relevant properties known?
Question 4: Can fuel and cladding be fabricated?

TABLE III-2 NUCLEAR THERMAL PROPULSION SUMMARY WORKSHEET (cont.)

REACTOR	FUEL	STRUCTURAL MATERIALS			TEMPERATURE (K)		**Q1	**Q2	**Q3	**Q4	READY LEVEL	CRITICAL TECHNOLOGY ISSUES
		Cladding	Coating	Matrix	Fuel	Exhaust						
Liquid Annulus	U,UC2		-	-	6000-7000	8000	No	Maybe	Some	N/A	1.0	Kinetics of liquid fuel containment, H2 compatibility liquid/gas separation
Liquid Core (Droplet Core)	U	W,Ta, carbides, C				3000-7000	Yes	-	Some	N/A	2.0	Kinetics of liquid fuel containment, H2 compatibility liquid separation, transport properties
Gas Core-Open Cycle A	U						Yes	-	Some	N/A	1.0	Fuel vapor containment & compatibility with wall & structural materials
Gas Core-Open Cycle B	U,UF4	HFC				3000-7000	Yes	-	Some	N/A	1.0	Fuel vapor containment & compatibility, wall & structural materials (U,Zr,Nb)C
Gas Core-Lite Bulb	UF6				~8000		Yes	-	Some	N/A	1.5	"Glass"/UF6 compatibility, "glass"/H2 compatibility

* Hydrogen is the propellant for all fuels listed with the following exceptions: Low Pressure Core Particle Bed Reactor: $H_2 + H$; NIMF: CO_2

** Question 1: Have fuels and materials been developed?
Question 2: Can fuels and materials be developed?
Question 3: Are relevant properties known?
Question 4: Can fuel and cladding be fabricated?

TABLE III-3 NUCLEAR ELECTRIC PROPULSION SUMMARY WORKSHEET

Walter ID	REACTOR	FUEL	STRUCTURAL MATERIALS			COOLANT	TEMPERATURE (K)		BURNUP, %	**Q1?	**Q2?	**Q3?	**Q4?	READY LEVEL	CRITICAL TECHNOLOGY ISSUES
			CLADDING	COATING	MATRIX		FUEL	CLADDING							
E1	SP-100	UN PINS	Re BONDED Nb-1Zr			Li	~1700	1400	10	YES	-	YES	YES	3.0	UN STABILITY AND FISSION PRODUCT INTERACTIONS
E8	PELLET BED	UC-ZrC	ASTAR, Mo, Re FRITS	ZrC	GRAPHITE	He	>3000	~2300		NO	YES	SOME	LIKELY	2.0	CORROSION BY HOT FLOWING HYDROGEN. STABILITY OF FUEL. COMPATIBILITY WITH FRIT MATERIAL
E5	NDR (Nerva Derivative Reactor)	UC2		SiC / ZrC	GRAPHITE	He-Xe		>1935	25	YES	-	YES	YES	5.0	HIGH BURNUP => MORE FISSION PRODUCT REACTIONS WITH FUEL, COATINGS. GRAPHITE INTEGRITY @ HIGH FLUENCE.
E7	PARTICLE BED	UC2	Re & Mo FRITS	SiC/ZrC		He-Xe		1500-2000	~35	YES	-	SOME	LIKELY	3.0	HIGH BURNUP => MORE FISSION PRODUCT REACTIONS WITH FUEL & COATINGS. MECHANICAL STRENGTH OF COATINGS
E2	TUBE REACTOR	UN	W-Re			Li	1700	1650	3	YES	-	SOME	LIKELY	2.0	LOSS OF NITROGEN; COOLANT COMPATIBILITY WITH FUEL AND CLADDING.
E3 & 10	CERMET REACTOR	UN			W-Re	Li	1670	1550	25	YES	-	SOME	YES	2.5	COMPATIBILITY, FUELS PROPERTIES; HI BURNUP => MORE FISSION PRODUCT REACTIONS WITH CERMET. FABRICATION.
E6	UTVR (Gas Core) MHD power cycle	UF4/KF				-	4000		50+	YES	-	FEW	N/A	1.0	VAPOR CONTAINMENT AND COMPATIBILITY WITH STRUCTURAL MATERIALS.
E11	GAS CORE REACTOR Dynamic Cycle					He	1960			YES	-	FEW	N/A	1.0	VAPOR CONTAINMENT AND COMPATIBILITY WITH STRUCTURAL MATERIALS.
*	URANIUM DROPLET CORE Metal Vapor Reactor	U				Na (vapor)	2500			YES	-	FEW	N/A	1.0	VAPOR CONTAINMENT AND COMPATIBILITY WITH STRUCTURAL MATERIALS.
E9	THERMIONIC REACTOR	UO2 Pellets	W-HfC			NaK, Li	~2200	1800-2400	4	YES	-	SOME	LIKELY	3.0	EMITTER / CLAD HIGH TEMPERATURE COMPATIBILITY WITH FUEL or Cs. EMITTER CREEP.

* Not used in questionnaire

**Question 1: Have fuels and materials been developed?
Question 2: Can fuels and materials be developed?
Question 3: Are relevant properties known?
Question 4: Can fuel and cladding be fabricated?

IV. COMPILATION OF DEVELOPMENT ISSUES

IV.1 Methods and Objectives

An important task that was assigned to the Panel at its inception was to develop in a very short time a consensus on the testing (within major facilities) that would be required to support the development of the NEP and NTP concepts that had been presented in the workshops from the fuels and nuclear materials standpoint.

For each of the concepts we prepared a list of issues, primarily from a fuels and materials point of view, that need to be addressed in a reactor development program. These issues, which eventually numbered 166, were grouped into five categories: Performance (57); Fabrication (42); Ex-Reactor tests (25); In-Reactor tests (19); and Facilities (23).

Twenty-six concept focal points (CFPs) were contacted and asked to fill out a questionnaire based on these issues. It was noted that not all the 166 issues applied to all concepts. Although our motivation was to assess the commonality of the facilities required among the concepts, a considerable amount of other significant data were obtained in the process.

We requested the concept focal points to provide their assessment of the importance of these issues by scoring the applicable ones from 5 to 1 (most to least important). Respondents could add issues as desired but were asked to work to a total of 200 points. Several scored over 200 and we used our judgment to scale their scoring down to 200. In the case of the SP-100-scale-up concept (E1) the submitted score was 72. This scoring was maintained without change in our basic tabulation, but we dropped it from subsequent data manipulations. Nine responses each were received for NEP and NTP concepts from a possible 11 and 15, respectively. By forcing the score to 200 in each case, the total score cannot be used as a means of down-selection. Rather, the information can be used to extract the common problems with a majority of the concepts that could be tackled early in the technology development phase.

Results

All of the data obtained in our survey are included in Appendix D.

Summary data indicating the average score for each of the main categories for NEP and NTP concepts are shown graphically in Fig. 4-1. Note that the average scores for both NEP and NTP concepts are allocated by the CFPs similarly among the main categories.

In the order of decreasing score for all the concepts taken together, these main categories rank as follows: Performance, Fabrication, Facilities, Ex-reactor tests, and In-reactor tests. The NTP concept scores also follow this order, while for the NEP concepts, ex-reactor tests received a higher score than facilities. Various conclusions as to order of importance of these main categories may be derived from different treatments of the data. One method is described in Fig. 4-2.

Figure 4-2 displays the average scores for NEP and NTP concepts in a way that highlights the significantly important or not important main categories. The data plotted represent the ratios of relative main category average score (compared with the total concept score of 200) to the relative number of issues in the main category. Note that these ratios tend to be 1.0. In other words, on the average the CFPs agreed with the general distribution of issues within the main categories that we identified. There are four exceptions (i.e. where this ratio falls out of the range of 0.9 to 1.1.) that are informative: (1) Fabrication issues are relatively not as important and In-reactor tests are more important (according to the CFPs) for NEP concepts and (2) Facilities are of major relative importance for NTP concepts, while Performance issues are relatively less important. These stand-out results may have been anticipated because of the perceived difficulty of testing open cycle systems in an environmentally acceptable manner and the recent progress made in SP-100 fabrication issues.

For both NEP and NTP, in global issue ranking (Appendix D, Table D-3), the top scorers in the field of 166 issues were:

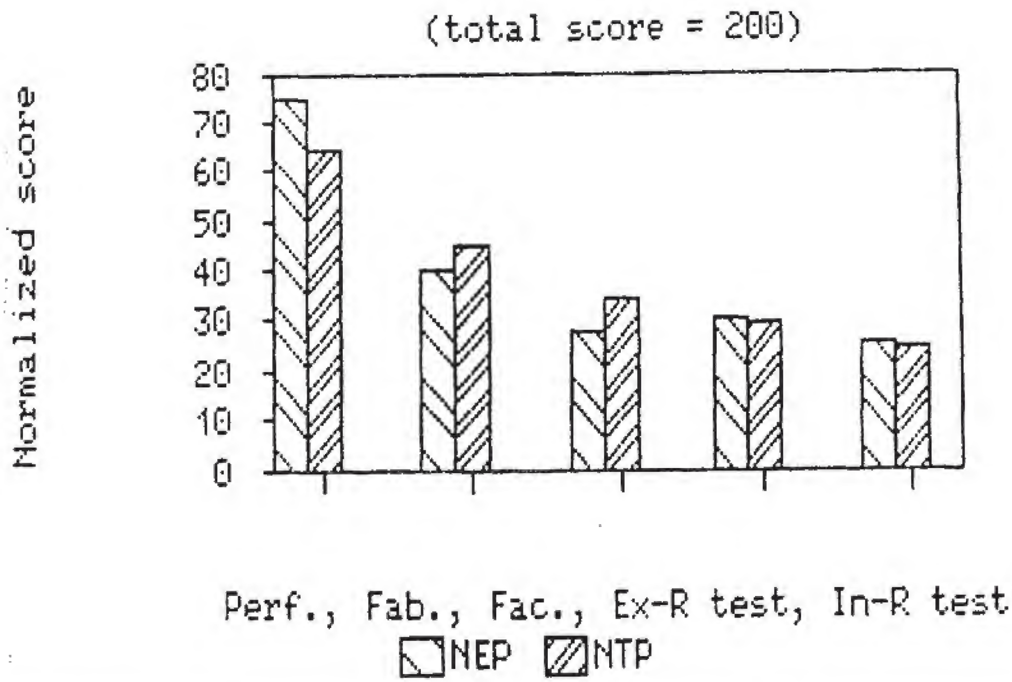


Figure 4-1 Main category normalized scores for NEP, NTP concepts as viewed by the CFPs

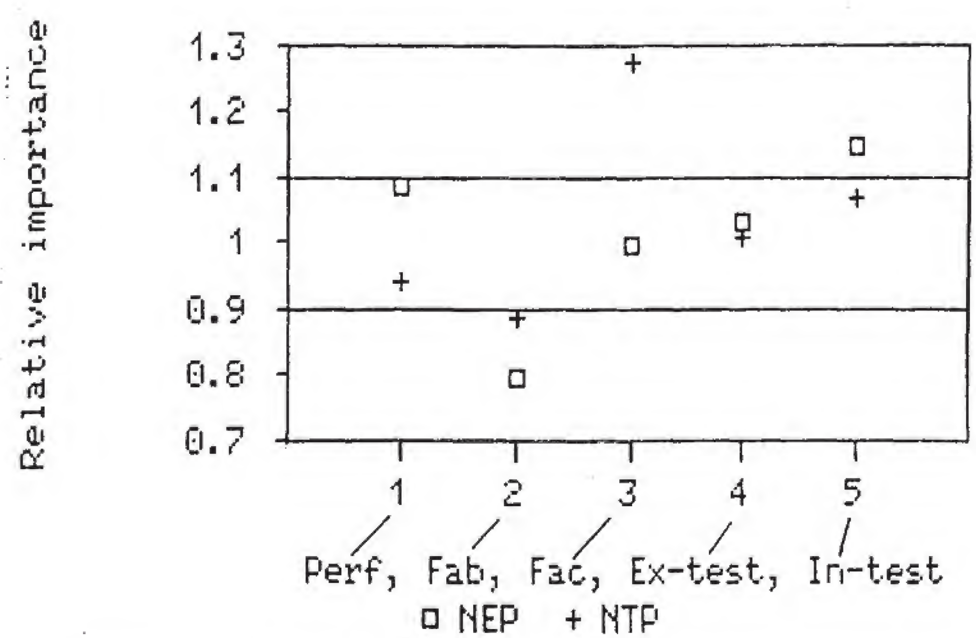


Figure 4-2 General relative importance of the main categories for NEP and NTP concepts

Property Measurement (62)

Materials Fabrication Facilities (56)

Integrated Ground Assembly Test (51)

Instrumented Fuel Element Tests (50)

These top scores were followed by the remaining 162 issues as shown below:

Score	Number of Issues
40 - 49	19
30 - 39	20
20 - 29	30
10 - 19	43
1 - 9	50

For NEP concepts only, in global issue ranking, the top scorer in the same field of 166 issues is:

Irradiation Induced Phenomena (33)

This top issue is followed by:

Score	Number of Issues
20 - 29	17
10 - 19	55
0 - 9	93

For NTP concepts only, in global issue ranking, the top scorers in the field of 166 issues are:

H2 Compatibility (36)
Hot Hydrogen Testing (36)
Property Measurement (34)
Integrated Ground Assembly Test (34)
Materials Fabrication (32)
Instrumental Fuel Element Tests (31)

When ranked within the main categories the top scorers are as follows:

Both NEP and NTP:

- Performance
  - Transient & Off-Normal Performance (47)
  - Neutronics & Control (47)

Irradiation Induced Phenomena (45)
Fission Product Release (43)
Component Mech & Chem Compatibility (43)
Fuel Element Integrity (43)
Rad-Hard High-Temp Electronics (43)
Composition Stability (42)
High-Temperature Thermometry (42)
H2 Compatibility (41)
Coating Integrity & Stability (40)

- Fabrication
  - Coating Technologies (43)

- Ex-Reactor Tests
  - Property Measurement (62)
  - Thermal Stress Testing (46)
  - Launch Vibration Tests (43)
  - Transient Testing (43)
  - Hot Hydrogen Testing (40)

- Facilities
  - Materials Fabrication (56)
  - Integrated Ground Assembly Test (51)
  - Fuel Fabrication & Assembly (Cermet) (47)

- In-Reactor Tests
  - Instrumented Fuel Element Tests (50)
  - Safety Tests (To Failure) (49)

For NEP alone:

- Performance
  - Irradiation Induced Phenomena (33)

- Fabrication
  - Low-weight, High-Temp Radiators (24)
  - Joining refractory metals (20)

- Ex-Reactor Tests
  - Property Measurement (28)
  - Heat Pipe Performance Testing (25)
  - Transient Testing (20)

- In-Reactor Tests
  - Safety Tests (To Failure) (25)
  - Transient & Off-Normal Tests (24)

- Facilities
  - Material Fabrication (24)
  - Fuel Fabrication & Assembly (21)
  - Properties & Characterization Laboratory (21)

For NTP alone:

- Performance
  - Mid Band Corrosion/Cracking (36)

- Fabrication
  - Coating Technologies (29)
  - QA & QC (24)
  - Carbon-Carbon Composites, Refractory (22)
  - Extrusion & Firing or Hot Pressing (20)
  - Thermocouple Alloy Development (20)

- Ex-Reactor Tests
  - Hot Hydrogen Testing (36)
  - Property Measurement (34)

- In-Reactor Tests
  - Instrumented Fuel Element Tests (31)

- Facilities
  - Integrated Ground Assembly Test (34)
  - Materials Fabrication (32)

In general, the concept focal points endorsed the judgment of the panel members. Thus, the importance of irradiation induced phenomena, property measurements, and safety tests to failure ranked high for NEP while mid-band corrosion cracking and hot hydrogen testing ranked high for NTP. The results of the survey were not without their surprises; for example, in-reactor tests were ranked below all other groups! We believe that the questionnaire could be better designed for future use. We believe that priorities for facility construction and facets of the reactor development programs could be guided with a more refined version of this approach. We recommend a variant of this procedure be used in the future to assist in detailed planning.

V. OVERVIEW OF FUELS AND MATERIALS DEVELOPMENT

The quest for higher performance (increased I_{sp}) of nuclear propulsion systems leads to the requirement for higher reactor operating temperatures. The severe operating conditions--high temperature, corrosive atmosphere, high radiation fluxes for NTP systems and a somewhat lower temperature for significantly longer time and higher burnup for NEP systems lead to a series of complex fuels and materials development issues. Since system lifetime (to be demonstrated with high reliability) is a major issue in manned spaceflight, the achievable peak fuel temperatures will be limited by mechanisms that degrade fuels and materials under these operating conditions. This is well depicted in the schematic plot of lifetime vs fuel temperature in Fig. 5.1, developed by Matthews and Stark.[1] At "low" temperatures, long fuel lifetimes can be expected, the life limiting condition being associated with high burnup and the concomitant swelling, chemical interactions, and mechanical stresses. At higher temperatures the anticipated lifetimes are progressively reduced because of a variety of mechanisms until fuel melting occurs, which effectively sets an upper limit on "conventional" solid core systems. Under practical conditions, of course, temperatures somewhat less than melting would form a realistic upper limit.

We note that in some of the advanced propulsion concepts, e.g. the liquid core and gas core concepts proposed, melting point restrictions are avoided by allowing the fuel to be molten or in vapor form. In these cases fuel form integrity is replaced by the requirement of fuel containment.

Current Status

In a general sense a technology development plan is based on three elements.

a) Current status of technology.

b) Definition of technology level required for missions.

c) Incremental development required to go from a) to b).

Table V.1 summarizes the present status of fuels technology as it applies to NTP and NEP. The ROVER/NERVA program attained several significant temperature and lifetime milestones. While there are questions about "recapture of the technology," we will assume that this level is current technology for NTP. Alternative concepts

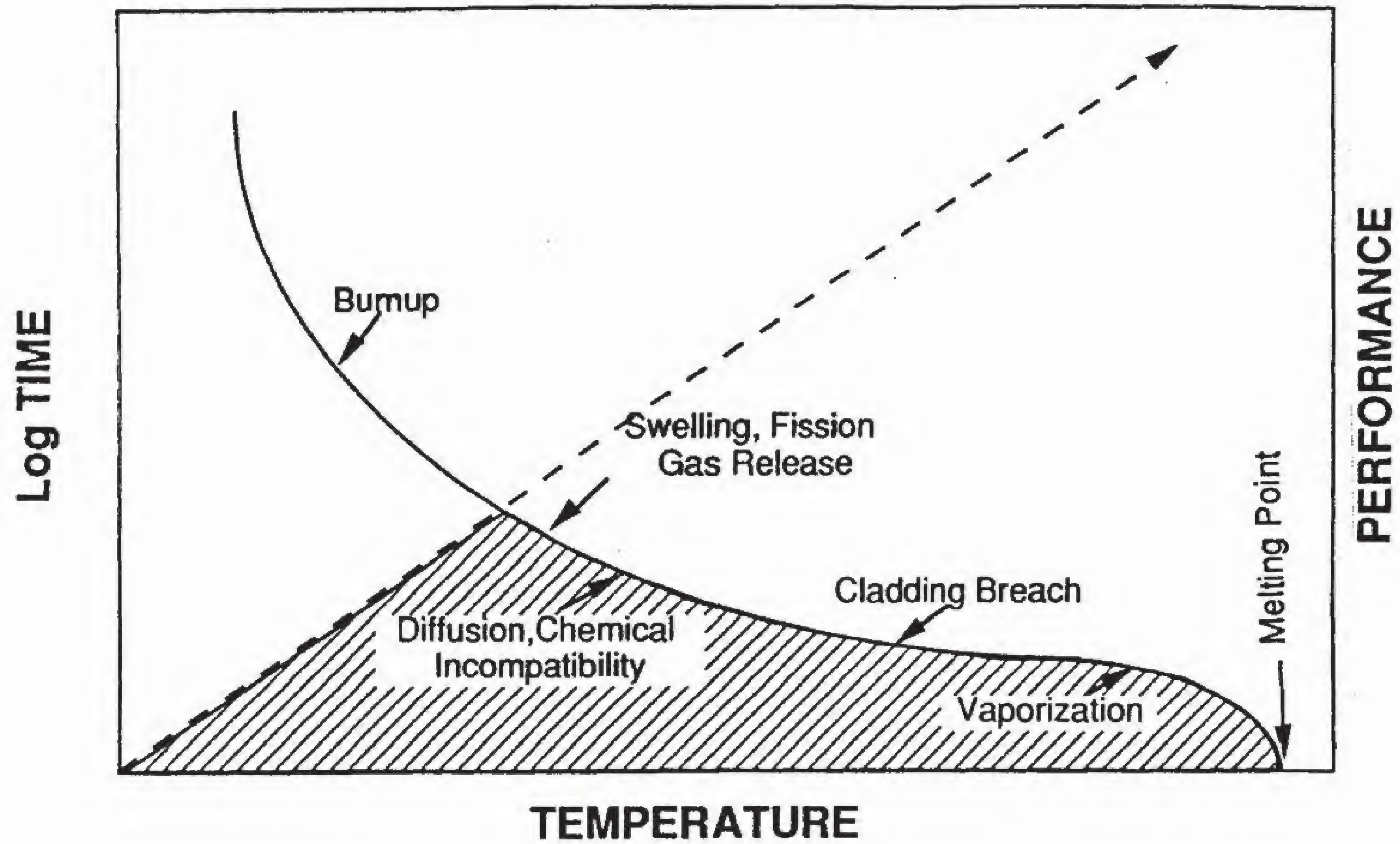


Fig. 5-1 **CONCEPTUAL TRADE OFF BETWEEN PERFORMANCE AND EFFICIENCY**

The shaded area represents feasible operating times and temperatures. The dashed line is a measure of the specific impulse. Fuel composition and melting point will change during reactor operation by evaporation, corrosion, diffusion, fission product migration, and chemical interactions.

TABLE V.1 STATE-OF-THE-ART PARAMETERS

APPLICATION	SYSTEM	FUEL TYPE	COATING/ CLAD	TEMP. K	LIFETIME	# OF CYCLES
NTP	ROVER/ PEWEE-1	Dispersion	ZrC	2555	40 min	1
NTP	ROVER/ NF-1	Composite Solid Solution	ZrC	2450	109 min	6
NEP	SP-100*	UN	Nb-1Zr/Re	1475 K Clad)	6 a/o burnup (Equivalent to 7 yr life @ 100 KWe)	Up to 5

* Not a system test

need to exceed these levels to be competitive, or be significantly superior in other attributes of interest.

Recent SP-100 results form the current status of NEP technology, even though they represent individual fuel pin and clad tests unlike the ROVER/NERVA data which refer to system tests.

Recent information from the Russians[2] suggest that they have attained temperatures (exit gas?) of 3000 K in their test rocket engines. While available details were scanty, there were references to solid solution carbide fuels (UC-ZrC, UC-ZrC-NbC) and heterophase compositions (ZrC-UC+C). Information on the lifetimes achieved at this temperatures was unclear. Reportedly, 4000 s of test times were achieved, but it was unclear whether the entire time was at 3000 K. There are also references to the production of very high temperature carbide solid solution fuel[3]--but indications are that these are highly unstable and would not be able to reach the desired lifetime goals.

There are materials data from a number of past and current programs that, taken as a whole, form the present materials "state-of-the-art." The data are discussed in detail in Section VII.

Stability Considerations for High Temperature Fuels

The task of extending the fuels and materials technology level to the required operating conditions is daunting. With the exception of the ROVER/NERVA derivative concept, all other concepts are characterized by considerably less work on fuels and materials and, therefore, represent considerably higher risk. A popular approach among concept developers has been to examine phase diagrams and conclude that binary and ternary carbides provide the highest potential for high temperature capability. In fact, one of the concepts presented had a coolant exit temperature of 3600 K based solely on the reported melting temperature of HfC. Those need to be viewed with caution since the stability of many of the binary and ternary compounds is open to question. In assessing fuel behavior the following general points should be noted.

1. Although most fuels suffer from the same types of degradation, the level of acceptable degradation in a given property varies strongly from fuel to fuel. (For example, compositional stability and hydrogen compatibility are problems of very different degrees of severity for the three carbide fuel types, e.g. UC_2 dispersed in graphite, binary fuels and ternary fuels.)
2. The limitations in performance and the degradation of high temperature nuclear fuels are more often associated with chemical stability rather than with nuclear effects. Chemical instabilities in ternary materials are more prevalent and more complex than chemical instabilities in binary materials.
3. Limitations in the performance of a fuel are often determined by interactions between fuels and coatings rather than by individual properties of the fuel material or individual properties of the fuel coating. The number of possible interactions between coatings and fuels in ternary fuel systems exceeds that in binary fuel systems.
4. Existing data support the claim that the complexities of the degradation processes appear monotonically related to the complexities of the materials, i.e., degradation in ternary materials is more complex than in binary materials and degradation in binary materials is more complex than in simple compounds such as UC_2.
5. High temperature nuclear fuel materials have important properties (including melting temperatures) that are geometry and mass dependent. Existing literature is based almost exclusively on binary materials. Virtually nothing is known about changes due to inherent stability in ternary materials. Because of the geometry and mass dependence of important properties, the absence of theory and data for the degradation processes in systems using ternary materials prevents significant extrapolation or scaling of required measurements. The properties and degradation reactions must be studied under realistic conditions.
6. A large number of interrelated factors are needed to determine the temperature-time properties and limitations of nuclear fuels. The fuels undergo time dependent-compositional and structural changes when subjected to temperature

cycles and temperature gradients. Such changes can lead to complex reactivity differences in gas environments and the development of time varying internal stresses that are position dependent and composition dependent. Such effects limit the performance of high-temperature fuels. Understanding the theoretical causes of these effects is necessary in their minimization. Minimization of the effects is important in reducing the degradation rates of both nuclear fuels and protective coatings. At present, insufficient information exists to predict temperature-time performance limits of solid core nuclear fuels.

A great deal of evidence exists that properties of important high temperature materials used in nuclear fuels and fuel element protective coatings have been obtained from nonequilibrium phase diagrams and that the materials themselves are thermodynamically unstable. These data are time dependent and should be used with caution.

Multicomponent solids at high temperatures have defect stabilized equilibrium structures that can exhibit large deviations from stoichiometry. At high temperatures, almost all stoichiometric refractory carbides and nitrides are unstable and evaporate incongruently. In closed systems, incongruently evaporating materials eventually achieve stable configurations that are inherently mass and geometry dependent. These mass geometry-dependent properties include melting temperatures.

Many nonequilibrium stoichiometric compounds yield apparent melting points when heated rapidly while exhibiting incongruent vaporization hundreds of degrees below the reported melting points. Experiments show that the composition of nonstoichiometric single-phase solids that are in equilibrium with the same vapor composition can differ from the nonequilibrium time-dependent stoichiometric melting compositions by more than 50% (e.g. Lyon has shown that the congruent composition of tantalum carbide is below $TaC_{0.6}$).

Equilibrium congruent vaporization compositions of nonstoichiometric nuclear fuels and fuel coatings are temperature dependent. The materials exhibit a wide range of evaporation rates at high temperatures. They undergo time dependent compositional and structural changes when subjected to temperature cycles and temperature gradients. Such changes can lead to complex reactivity differences in

gas environments and the development of time varying internal stresses that are position and composition dependent. Such effects limit the performance of high temperature fuels. Nuclear fuels and fuel coatings made of intrinsically nonstoichiometric materials are unstable under most conditions of operation. They decompose by evaporation during use. The properties of such materials are temporal and generally unpredictable. These materials can only be successfully used in reactor designs if the parameters that reduce the degradation rates to acceptable levels can be established.

Experience from chemical kinetic studies of nonstoichiometric binary materials shows that a large number of parameters are involved in pertinent property changes. These include many poorly understood structural and metallurgical variables which define macroscopic and microscopic properties. These variables require control for reproducible preparation of acceptable nuclear fuels and fuel coatings.

Temperature gradients in both the fuels and fuel coatings cause compositional instabilities that are peculiar to nonstoichiometric solids. The freezing points of fuel solutions are composition dependent. In incongruently evaporating systems where the final equilibrium compositions are dependent upon mass and volume, the freezing point compositions will be dependent upon mass and the volume which encloses the vapor. If such materials are used as nuclear fuels, geometries which allow control of the fuel vapor volumes have important advantages.

Existing literature is based almost exclusively on binary materials. Virtually nothing is known about changes due to inherent stability in high defect content ternary materials. Consequently, a great deal of high temperature-high pressure work will be required to understand and reduce degradation in systems utilizing ternary materials.

Appendix E[4] presents a more detailed discussion of these points (a list of references is included in the Appendices). We emphasize that it is not sufficient to point to a phase diagram as the basis for high temperature fuel design. A considerable amount of work on fuel composites is needed before their behavior can be characterized.

Release of Fission Products

The issue of fission product retention needs some discussion. The Safety Policy Panel took a general position on the question of "acceptable" fission product releases, with the recommendation of "ALARA." The significance of releases will be different for NTP and NEP systems in a technical sense because of the operational differences between the two systems. For NTP the question of the effect of releases during operations in space is not resolved, but there is some evidence that the impact will be small since the effluents are unlikely to recirculate into the spacecraft. The effect of releases during the ground test is likely to be more important since this will dictate the nature and complexity of the effluent treatment system.

For NEP the fission product releases will affect operations since there could be plateouts and depositions (via the circulating coolant) that might result in high local doses. The extent of the releases are affected by operating temperature (considerably lower than that for NTP) but more by higher fuel burnup which can create pathways for fission product release. Data for fission product retention at the NEP temperatures envisaged are limited and clearly considerable effort needs to be expended in quantifying the burnup behavior of the fuels. The design of the fuel elements themselves could be impacted severely by such experimental work (incorporation of real fission product transport barriers may be required). Thus, the question of retention of fission products could be an important driver in NEP fuel choices.

Categorization

As stated under Assumptions (Section I.4), the fuels and materials of potential interest to nuclear propulsion of space vehicles comprise a large number of technologies in diverse states of readiness. At the present time comparative evaluation of the proposed schemes is difficult and reaching consensus on these comparisons is nearly impossible. The performance and time-to-develop predictions are often based upon extrapolations of theoretical plausibility arguments and preliminary feasibility tests. Furthermore, the predicted or anticipated performance in the literature has been derived from non-comparable assumptions.

It is clear to the Panel that a broad range of fuels and materials technologies needs to be considered at this stage since the "proven" NERVA technology is at the

low end of requirements for SEI missions. The technologies identified in this evaluation are judged by the Panel to merit serious consideration in SEI program plans. It is not possible at this time to comparatively evaluate the technologies for development risk--that is to quantitatively evaluate the likelihood that, given adequate funding, the technology can be successfully developed without unanticipated findings that would prevent successful implementation. Thus, the reader is cautioned not to infer a ranking among technologies beyond the general categorizations explicitly stated by the Panel. Judgment between technologies cannot be made on single attributes (unless these attributes prove to be "fatal"); indeed it requires detailed cost-benefit and systems analyses that have not been undertaken.

With these caveats, it is still necessary to "categorize" concepts such that a manageable set of fuels and materials are developed in the time frame of interest. It is clear that there will be insufficient funding to pursue all concepts. The purpose of categorization is to maximize the probability of successful development of a useable set of fuels and materials within assumed constraints of budget and time.

It is clear that fuels/materials issues will form only one set of criteria and that systems level issues will be significant drivers in the future downselection decisions. It is also clear that there are really two levels of categorization of fuels and materials:

a. a basic set of filters to select fuels and materials that could reasonably be in contention, and

b. a more complex set of filters to select the best candidates for the flight system.

With these guidelines in mind, we established the following preliminary criteria. The criteria are summarized in Table V.2.

1. <u>Time at Temperature Capability</u>

<u>Fuels</u>

NTP $\geq$ 2500 K for > 10 hours

In appropriate environment (H_2, contact material, etc.).

NEP $\geq$ 1500 K for 7 years

In liquid metal or gas environment.

TABLE V.2 FUELS AND MATERIALS "CATEGORIZING" CRITERIA

- <u>Time at Temperature</u>
  - <u>Fuels</u>
    - NTP $\geq$ 2500 K for > 10 hr (in appropriate environment)
    - NEP $\geq$ 1500 K for 7 yr (in liquid metal or gas environment)
  - <u>Materials</u>
    - Corresponding to above
- Fabricability
- Fission Product Containment
- Radiation Tolerance
- Mechanical Properties
- Consistent with TRL-6 by 2006

For materials, the temperatures correspond as appropriate to these temperatures.

It is noted that the current SP-100 fuels fall below the condition stated above. It was decided to leave the condition as it is since the SP-100 fuel/materials development was ongoing and the criteria referred to new items.

2. <u>Fabricability</u>

Fuels and materials fabricability need to be assessed. It needs to be emphasized that fabricability refers to an extrapolated capability rather than just present capability.

3. <u>Fission Product Containment</u>

Fission product containment will be an important criterion. The degree of

fission product retention over operating life will affect a number of system design selections.

4. Radiation Tolerance

   Acceptable materials behavior under the anticipated fluences will need to be demonstrated.

5. Mechanical Properties

   Mechanical properties at elevated temperatures must meet requirements in the correct environment for the appropriate time.

References

1. Internal LANL Nuclear Propulsion Fuels Report, 1990.

2. A.Y. Goldin, et al., "Development of Nuclear Rocket Engines in the USSR," presented at the AIAA Propulsion Meeting, June 1991.

3. Private communication to S.K. Bhattacharyya, November 1991.

4. The Appendix is based upon a paper to be published in Nuclear Technology. The author, D.H. Schweitzer of BNL, has agreed to include the contents of the paper in the report.

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VI. FUELS TECHNOLOGY DEVELOPMENT PLAN

Introduction

With all of the caveats listed in Section II, the present state-of-the-art in NTP and NEP fuels technology in the U.S. can be considered to be based upon the ROVER/NERVA and SP-100 programs respectively. The technology development plan focuses on the incremental actions required to increase the technology status for those levels to the higher levels necessary to meet SEI requirements.

The material in this section is organized as follows. The technical issues for each of the major class of fuels are discussed first. The testing approach to resolve the issues and to develop the required property and safety related data is presented next.

VI.1 Technical Issues

An early investment in fuels development would pay off by bringing up the readiness levels of some of the advanced, high specific impulse concepts. It should be stated that the first concepts discussed here all have the potential to contribute to SEI missions. While each has its strengths, there are areas where development is required to permit assurance of performance and/or safety. Review of the issues shows that they can be grouped by reactor type and initial development activities can be simultaneously aimed at several concepts. This is important since a good strategy is to maximize the number of options available within the anticipated budget constraints.

VI.1.1 Nuclear Thermal Propulsion (NTP)

Prismatic Solid Carbide Core Reactors: The technical feasibility issues for the prismatic carbide solid core fuels are listed in Table VI.1. These feasibility issues are presented for UC_2 dispersed in graphite, (U, Zr)C plus graphite composites, and ternary or binary solid solutions. The dispersed UC_2 and the composite fuels were used in NERVA engines and in the Nuclear Furnace respectively (Fig. 6.1). The issues involved with both of these fuels are concerned with the maximum time/temperature capability involving corrosion, cracking, compatibility, fission product release, and

TABLE VI.1
ISSUES AND REQUIREMENTS FOR ROVER/NERVA NTP FUEL DEVELOPMENT

ROVER/NERVA	DISPERSED FUEL	COMPOSITE FUEL	SOLID SOLUTION FUEL
Critical Technical Issues	Maximum time/temp capability Mid band corrosion/cracking H2 compatibility Coating integrity and stability Cycling capability Fission product release Component compatibility Element/Element interactions	Maximum time/temp capability Mid band corrosion/cracking H2 compatibility Coating integrity and stability Cycling capability Fission product release Component compatibility Element/element interactions	Maximum time/temp capability High temperature/vaporization Melting point Composition stability H2 compatibility Cycling capability Irradiation induced phenomena Component compatibility
Fabrication Issues	Recapture Rover/NERVA technology Sphere fabrication (new processes) High CTE graphite Extrusion and firing Coating technologies Joining QA and QC	Recapture Rover/NERVA technology Phase distribution High CTE graphite Extrusion and firing or hot pressing Coating technologies Design flexibility Joining QA and QC	Develop new process Homogeneous solid solution Forming and sintering Characterization Design flexibility Joining QA and QC
Crucial Ex-pile Tests	Property measurements Characterization Cycling tests Hot hydrogen testing Element interaction tests	Same as "dispersed fuel" tests	Same as "dispersed fuel" tests
Irradiation Testing	Instrumented fuel element tests Single element tests (same as instrumented tests) Statistical tests Transient and off-normal tests Prototypical assembly tests Safety tests (to failure) Particle or fuel sample irradiations	Same as "dispersed fuel" testing	Same as "dispersed fuel" testing
Facilities Requirements	Fuel fabrication & assembly facility Properties & characterization lab Hot gas testing lab Single element test reactor (same as instrumented irradiation test loop) Instrumented irradiation test loop Transient reactor Nuclear furnace	Same as "dispersed fuel" requirements	Same as "dispersed fuel" requirements

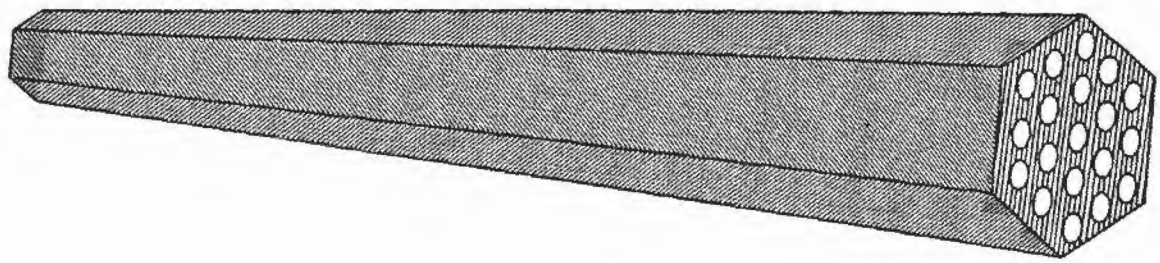

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Figure 6.1 NERVA Fuel Element

element/element interactions. Similar issues are involved with the solid solution fuels, for which there are additional concerns of high-temperature vaporization, melting points, and composition stability.

The UC_2 dispersed fuels exhibited extensive fuel loss from corrosion during engine testing but during the Nuclear Furnace testing, the composite fuel may have exhibited better performance. The fuel loss is attributed to the reaction of hydrogen with the uranium carbide fuel as a result of cracks in the zirconium carbide coatings; this was the so-called "mid-band corrosion" discovered during engine testing. The development of the fuels through special composition or through the use of coatings is required to improve the corrosion resistance of the fuels with hydrogen propellents.

Apart from the inherent ability of carbide fuels to retain fission products, composite and solid solution fuels do not include any additional design features to retain fission products. The required times at high temperatures will determine the amount of fission product release from these fuels.

The solid solution binary and ternary carbide fuels offer potentially higher melting points, and hence, higher specific impulses than those of fuels previously used in the ROVER and NERVA programs. These fuels have the same technical feasibility issues as the other fuels discussed above, but they also have issues of high-temperature vaporization, melting points, and compositional stability. Early work by Tosdale[1] indicated that ternary carbides of uranium, zirconium, and niobium could attain melting points of 3600 K. However, his work needs to be verified since the experimental approach suggests the results may be between the solidus and liquidus temperatures. There are potential problems of high vaporization rates and stability of the composition with both temperature and irradiation for the binary and particularly the ternary fuels.

The use of coatings may extend the operating temperatures and/or times for the fuel. However, the stability and compatibility of coatings on fuel rods need to be validated to insure improved performance. Of special interest are thermal expansion parameters, thermal conductivity, and resistance to thermal stress. Fuel/coating/coolant compatibility testing with H_2, H, and CO_2 needs to be started to evaluate the viability of dissociated hydrogen and indigenous propellants relative to molecular hydrogen. Russian data[2] also show a degradation of the carbides with the formation

of free carbon (and concomitant reduction of carbide stoichiometry) at high temperatures over relatively short times.

Particle Bed Solid Core Reactors: Issues were identified for the uranium carbide fuel coated with multiple layers of graphite with an external coating of zirconium carbide, and for the advanced solid solution binary and ternary fuels. The feasibility issues listed in Table VI.2 are centered on particle integrity, fuel element integrity, and power/coolant mismatch. Other issues are fission product migration and release, cycling capability, coating integrity and stability, and element/element interaction. Many of these issues are expected to be addressed by the Air Force SNTP program. For the more advanced fuels based on binary and ternary mixtures containing uranium carbide, the same issues apply, but high-temperature vaporization and phase equilibria are also very important.

The flow through the particle bed fuel element may be controlled by the use of the very fine porosity or engineered flow paths (orificing) in the cold frit, or by porosity in the fuel bed (Figure 6.2). The PBR reactor concept presented by BNL at the NASA workshops uses pressure drop control by the cold frits, whereas the low pressure nuclear thermal rocket (LPNTR) uses the fuel bed for pressure drop control. Flow through fine porosity in the cold frits or in the fuel is complicated and not well understood at this time. There are regimes of flow instability that might occur at low or decay heat removal flows. The instabilities could be caused by the increased kinematic viscosity with temperature, given the fact that the flow near surfaces is nearly zero.

Fuel element integrity is based on the cold frit behaving elastically and the hot frit being rigid at operating temperature so, that when heated, the fuel expands outward deforming the cold frit. The hot frit needs to be rigid at operating temperatures to prevent any deformation of this component. Also this material requires a high critical stress intensity to prevent failure from the presence of any small cracks or defects. During cycling, there is also a potential concern that a bed of very small particles sandwiched between two concentric cylinders could result in particle bed "lockup" and thus impact the lifetime of these elements.

TABLE VI.2

ISSUES AND REQUIREMENTS FOR PARTICLE BED REACTOR DEVELOPMENT--FUELS DEVELOPMENT AND TESTING (NTP-PBR, LPNTR, PELLET BED)

PARTICLE BED	MONOCARBIDES	BINARY CARBIDES	TERNARY CARBIDES
Critical Technical Issues	Performance limits (20 kW/cm^3 and 2500K) Power/cooling matching and flow stability Particle mechanical and chemical compatibility Fission product migration and release Fuel element integrity (particle/frit interact) Cycling capability (dimensional stability) Coating integrity and stability H2 compatibility High-temperature vaporization Element/element interactions	Performance limits (20 kW/cm^3 and 3100K) Phase equilibria (MP) High temperature stability and vaporization Particle mechanical and chemical compatibility Fission product migration and release Power/cooling matching and flow stability Fuel element integrity (particle/frit interact) Cycling capability (dimensional stability) Coating integrity and stability H2 compatibility High-temperature vaporization Element/element interactions	Performance limits (20 kW/cm^3 and 3300K) Phase equilibria (MP) High temperature stability and vapoprization Particle mechanical and chemical compatibility Fission product migration and release Power/cooling matching and flow stability Fuel element integrity (particle/frit interact) Cycling capability (dimensional stability) Coating integrity and stability H2 compatibility High-temperature vaporization Element/element interactions
Fabrication Issues	Sol-gel sphere fabrication optimization Develop cryochemical sphere fabrication Hot and cold frit development Fuel and hot frit coating development Joining fuel element components Fuel element characterizations QA and QC	Develop cryochemical sphere fabrication Carbothermic reduction and sintering Homogeneous, solid solution Hot and cold frit development Fuel and hot frit coating development Joining fuel element components Fuel element characterizations QA and QC	Develop cryochemical sphere fabrication Carbothermic reduction and sintering Homogeneous, solid soltuion Hot and cold frit development Fuel and hot frit coating development Joining fuel element components Fuel element characterizations QA and QC

TABLE VI.2
ISSUES AND REQUIREMENTS FOR PARTICLE BED REACTOR DEVELOPMENT--FUELS DEVELOPMENT AND TESTING (NTP-PBR, LPNTR, PELLET BED)
(cont.)

PARTICLE BED	MONOCARBIDES	BINARY CARBIDES	TERNARY CARBIDES
Crucial Ex-pile Tests	Property measurements and characterizations Component mechanical and chemical interaction tests Transient heating testing of particles Hot hydrogen testing Pressure drop, flow resistant of frits and particle	Same as "monocarbides" tests	Same as "monocarbides" tests
Irradiation Testing	Particle irradiations (stability) Instrumented single fuel element tests Performance (<9.4 x 100cm) Statistical tests (reliability) Transient and off-normal tests Safety tests (to failure)	Same as "monocarbides" testing	Same as "monocarbides" testing
Facilities Requirements	Fuel fabrication and assembly facility Properties and characterization laboratory Hot gas testing laboratory Capsule irradiations Instrumented irradiation test loop Transient reactor Driver core Hot cells	Same as "monocarbides" requirements	Same as "monocarbides" requirements

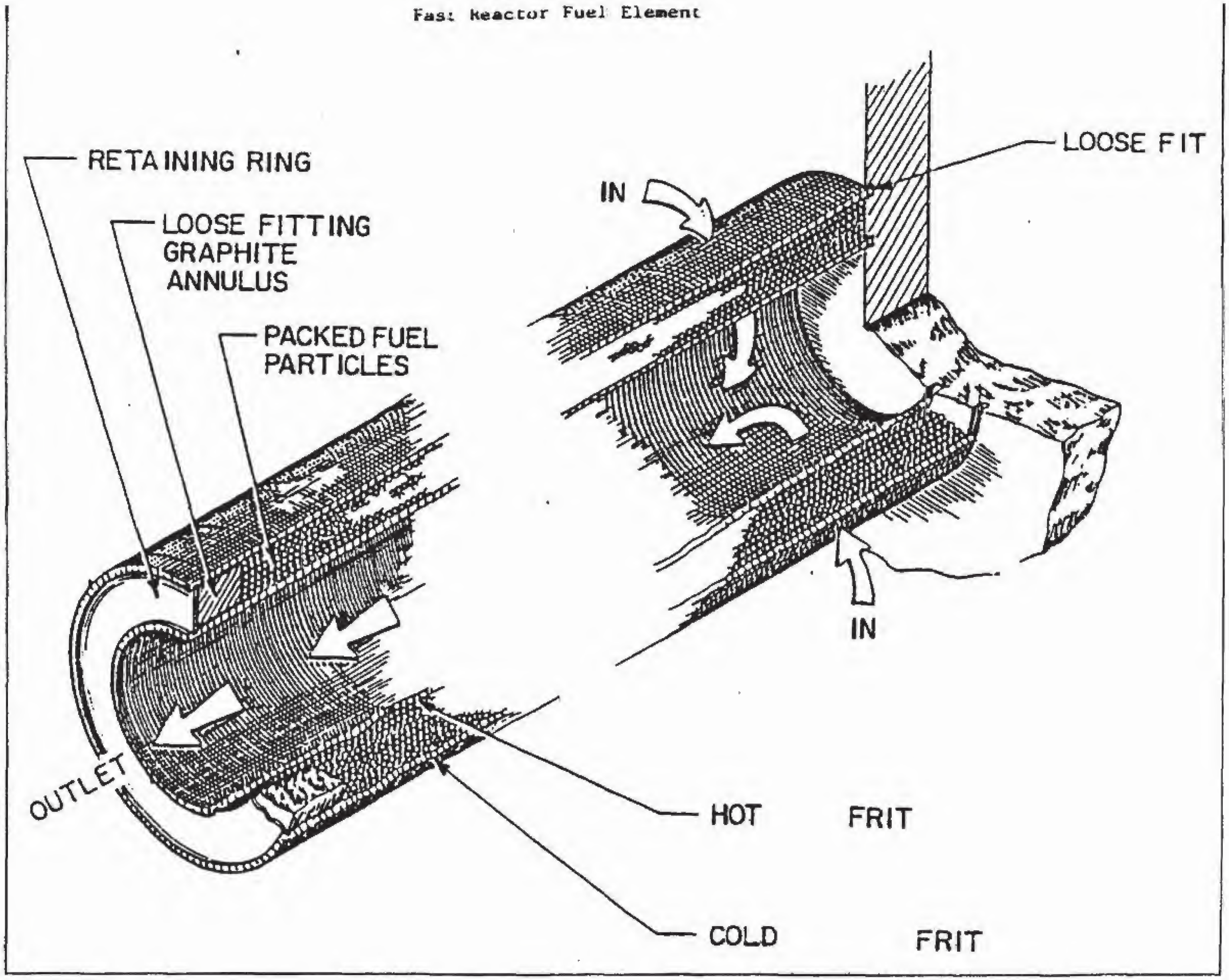

Figure 6.2 Particle Bed Fuel Element

Particle integrity is concerned with the chemical compatibility of the fuels with the frits, compatibility of the fuel with the coatings, compatibility of hydrogen with the coatings and with the fuel in case the coatings become cracked. At high operating temperatures, the coatings are prone to high temperature vaporization. The high surface area of the fuel, which makes the particle bed concept attractive from a heat transfer point of view, may also lead to higher mass loss in flowing hydrogen. As a result, new coatings development is needed, the kinetics of high temperature volatility and mass loss needs to be measured, and the mechanisms of degradation understood.

Very high temperature gradients across the fuel particle bed (resulting from the radial flow concept) lead to thermal migration of both fuel materials and fission products. Fission products could interact with the coatings resulting in the degradation of the coatings.

Prismatic Solid UO_2 Cermet Core Reactors: Technical feasibility issues for the prismatic UO_2 solid core fuels are listed in Table VI.3. The dispersed UO_2 fuels were initially developed in the GE 710 program and the ANL Nuclear Rocket Program (Figure 6.3), but underwent only limited irradiation testing. The issues involved with both of these fuels are concerned with the maximum time/temperature capability involving hydrogen and UO_2 compatibility with tungsten, fission product migration and release, the UO_2 stability and the potential migration of uranium in tungsten, the ductile brittle transition temperature (DBTT) in tungsten and tungsten-based alloy claddings, and element/element interactions.

The UO_2 cermet fuels are proposed to operate at temperatures up to 2800 K which is about 300 K below the melting point of UO_2 (depending on conditions such as purity, cover gas, etc.). At this point, the vapor pressure over UO_2 is very high as a result of numerous species UO_2, UO, and perhaps O_2 and U. U metal may diffuse into the tungsten resulting in liquid metal embrittlement of the tungsten. Along with the high-temperature vaporization, fission product release could be a problem with the vaporization and otherwise high-temperature operation of UO_2 fuels. Certain fission products such as cesium or barium tend to remain in the oxide fuels as oxide compounds, while others such as ruthenium and rhodium tend to the metallic form,

TABLE VI.3
ISSUES AND REQUIREMENTS FOR UO_2 CERMET FUEL REACTOR DEVELOPMENT--
FUEL DEVELOPMENT AND TESTING NTP

UO_2 CERMET FUEL	ISSUES AND ACTIVITIES

Critical technical issues	Performance limits
	    Up to 10 kW/cm^3 and 2800K fuel temperature
	    Safety margins for different failure modes
	Fission product migration and release
	UO_2/U stability and migration in W matrix
	Cycling capability (DBTT and stresses)
	Cladding integrity and stability
	    Ductile-brittle transition temperature
	    H_2 compatibility
	Element/element interactions
	    Bowing (dimensional stability)
	    Failure propagation

Fabrication Issues	Recapture cermet fuel technology
	    Machining
	    Joining
	    Fuel fabrication
	Develop UO_2 cryochemical sphere fabrication
	Develop advanced fuel element fabrication
	    Fuel coating technology
	    Fuel/matrix pressing and sintering
	    Hot isostatic pressing of element
	Fuel and Element characterization
	QA and QC

Crucial Ex-pile Tests	Property measurements and characterizations Cyclic testing Hot hydrogen testing Cermet interaction testing

Irradiation Testing	UO_2 particle irradiation (fission product)
	Cermet sample (fission production and stability)
	Instrumented fuel element tests (4.75 x 87)
	    Performance
	    Statistical tests (reliability)
	    Transient and off-normal tests
	    Safety tests (to failure)

Facilities Requirements	Fuel fabrication and assembly facility Properties and characterization laboratory Instrumented irradiation test loop Hot gas testing laboratory Transient reactor Hot cells

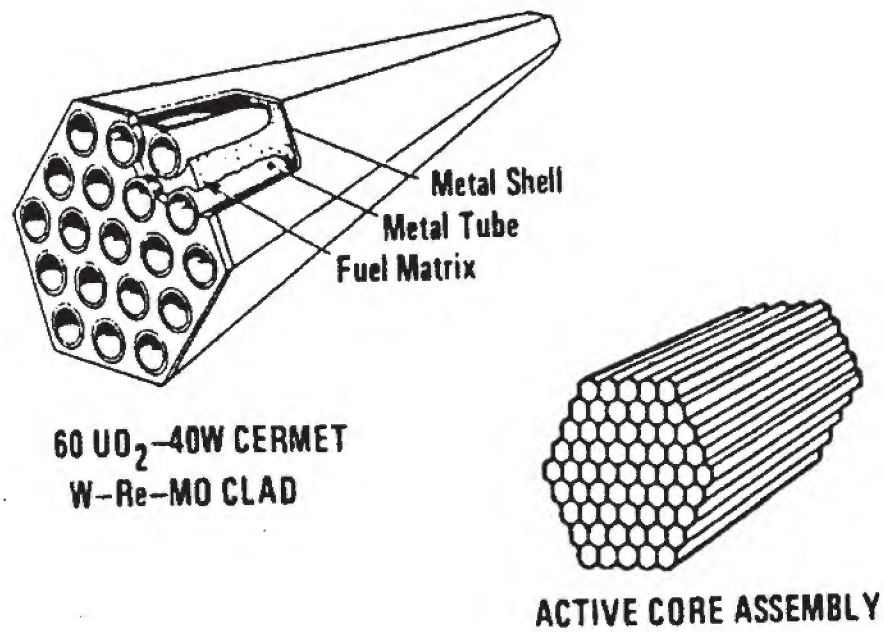

Figure 6.3 UO_2 Cermet Fuel Element

and diffuse out of oxide fuels. Grain growth and thermal cycling have been seen to cause fission fragment release along grain boundaries. How well the fission products are retained in the fuel and in the tungsten matrix without excessive stresses from the fission gas accumulation needs to be determined.

As mentioned earlier, tungsten is a body-centered-cubic metal and is characterized by a ductile-to-brittle-transition temperature (DBTT). The DBTT in tungsten is increased with an increase in grain size and changes can be as high as 500 K. The existence of a low DBTT imposes restrictions on the temperature ramp rate of the fuel elements and the associated thermal stresses. It needs to be emphasized that in TREAT tests, ramp rates of 16,000 C/sec were imposed on UO_2-W cermets and no failures were observed. This was true under repetitive transient operations. Thus, there are indications that this problem might not be serious. Also, some safety implications surround the potential fracturing of the elements in the unlikely event of an unplanned reentry. A major advantage of tungsten is that it has the lowest vapor pressure of all of the refractory metals under consideration.

The fuel element/element interactions involve element bowing and dimensional changes that could affect the neutronic response of the core and possible cooling of the elements.

VI.1.2 Nuclear Electric Propulsion (NEP)

Prismatic Solid Carbide Core Reactors: The technical feasibility issues for the prismatic carbide solid core fuels are listed in Table VI.4. These issues are essentially the same as those for the NTP prismatic solid carbide fuels except the potential of burnup to 25 atom percent creates additional complications. Some data on the mixed carbides of uranium and zirconium indicate that the swelling may reach at high as 40% with burnup for temperatures over 1700 K.[3] There is some question as to the stoichiometry of the test fuel, and whether the swelling results are applicable to sub-stoichiometric carbide fuels.

Particle Bed Solid Core Reactors: The feasibility issues listed in Table VI.5 are the same as those of the particle bed fuels proposed for the NTP systems. Again the major difference from the NTP issues is the question of burnup to 25% discussed above.

TABLE VI.4
ISSUES AND REQUIREMENTS FOR ROVER/NERVA NEP FUEL DEVELOPMENT

ROVER/NERVA	DISPERSED FUEL	COMPOSITE FUEL	SOLID SOLUTION FUEL
Critical Technical Issues	Maximum time/temp capability Mid band corrosion/cracking H2 compatibility Coating integrity and stability Cycling capability Fission product release Component compatibility Element/Element interactions Burnup	Maximum time/temp capability Mid band corrosion/cracking H2 compatibility Coating integrity and stability Cycling capability Fission product release Component compatibility Element/element interactions Burnup	Maximum time/temp capability High temperature/vaporization Melting point Composition stability H2 compatibility Cycling capability Irradiation induced phenomena Component compatibility Burnup
Fabrication Issues	Recapture Rover/NERVA technology Sphere fabrication (new processes) High CTE graphite Extrusion and firing Coating technologies Joining QA and QC	Recapture Rover/NERVA technology Phase distribution High CTE graphite Extrusion and firing or hot pressing Coating technologies Design flexibility Joining QA and QC	Develop new process Homogeneous solid solution Forming and sintering Characterization Design flexibility Joining QA and QC
Crucial Ex-pile Tests	Property measurements Characterization Cycling tests Hot hydrogen testing Element interaction tests	Same as "dispersed fuel" tests	Same as "dispersed fuel" tests
Irradiation Testing	Instrumented fuel element tests Single element tests (same as instrumented tests) Statistical tests Transient and off-normal tests Prototypical assembly tests Safety tests (to failure) Particle or fuel sample irradiations	Same as "dispersed fuel" testing	Same as "dispersed fuel" testing
Facilities Requirements	Fuel fabrication & assembly facility Properties & characterization lab Hot gas testing lab Single element test reactor (same as instrumented irradiation test loop) Instrumented irradiation test loop Transient reactor Nuclear furnace	Same as "dispersed fuel" requirements	Same as "dispersed fuel" requirements

TABLE VI.5
ISSUES AND REQUIREMENTS FOR PARTICLE BED REACTOR DEVELOPMENT--FUELS DEVELOPMENT AND TESTING (NEP-PBR, LPNTR, and PELLET BED)

PARTICLE BED	MONOCARBIDES	BINARY CARBIDES	TERNARY CARBIDES
Critical Technical Issues	Perform limits (0.5 kW/cm^3 and 2500K) Power/cooling matching and flow stability Particle mechanical and chemical compatibility Burnup (<25%) Fission product migration and release Fuel element integrity (particle/frit interact) Cycling capability (dimensional stability) Coating integrity and stability H2 compatibility High-temperature vaporization Element/element interactions	Perform limits (0.5 kW/cm^3 and 2300K) Phase equilibria (MP) High temperature stability and vaporization Particle mechanical and chemical compatibility Burnup (<25%) Fission product migration and release Power/cooling matching and flow stability Fuel element integrity (particle/frit interact) Cycling capability (dimensional stability) Coating integrity and stability H2 compatibility High-temperature vaporization Element/element interactions	Performance limits (0.5 kW/cm^3 and 2500K) Phase equilibria (MP) High temperature stability and vapoprization Particle mechanical and chemical compatibility Burnup (<25%) Fission product migration and release Power/cooling matching and flow stability Fuel element integrity (particle/frit interact) Cycling capability (dimensional stability) Coating integrity and stability H2 compatibility High-temperature vaporization Element/element interactions
Fabrication Issues	Sol-gel sphere fabrication optimization Develop cryochemical sphere fabrication Hot and cold frit development Fuel and hot frit coating development Joining fuel element components Fuel element characterizations QA and QC	Develop cryochemical sphere fabrication Carbothermic reduction and sintering Homogeneous, solid solution Hot and cold frit development Fuel and hot frit coating development Joining fuel element components Fuel element characterizations QA and QC	Develop cryochemical sphere fabrication Carbothermic reduction and sintering Homogeneous, solid solution Hot and cold frit development Fuel and hot frit coating development Joining fuel element components Fuel element characterizations QA and QC

TABLE VI.5
ISSUES AND REQUIREMENTS FOR PARTICLE BED REACTOR DEVELOPMENT--FUELS DEVELOPMENT AND TESTING (NEP-PBR, LPNTR, and PELLET BED) (cont.)

PARTICLE BED	MONOCARBIDES	BINARY CARBIDES	TERNARY CARBIDES
Crucial Ex-pile Tests	Property measurements and characterizations Component mechanical and chemical interaction tests Transient heating testing of particles Pressure drop, flow resistant of frits and particle	Same as "monocarbides" tests	Same as "monocarbides" tests
Irradiation Testing	Particle irradiations (burnup and stability) Instrumented single fuel element test Performance (<7.5 x 100cm) Statistical tests (reliability) Transient and off-normal tests Safety tests (to failure)	Same as "monocarbides" testing	Same as "monocarbides" testing
Facilities Requirements	Fuel fabrication and assembly facility Properties and characterization laboratory Hot gas testing laboratory Capsule irradiations Instrumented irradiation test loop Hot cells	Same as "monocarbides" requirements	Same as "monocarbides" requirements

UN/W-Re Cermet Fueled Reactors: The technical feasibility issues for the prismatic carbide solid core fuels are listed in Table VI.6. These issues revolve around the UN/W-Re compatibility, burnup up to 25% accompanied with fission product migration and release, fuel swelling, safety margins, cycling capability and the ductile brittle transition temperature, and coating integrity. Performance up to 0.5 kW/cm^3 at 2200 K may be required.

The compatibility of the UN with the W-Re alloy may be a significant problem for this concept. Scoping tests have indicated that U from UN reacts with Re to form a brittle URe_2 which results in a volume expansion of nearly 100%.[4,5] This volume expansion and the accompanying stress could cause the cermet to lose structural integrity. Possible solutions are to reduce the fuel operating temperature or to develop a more stable nitride fuel by control of the UN stoichiometry or by doping.

The burnup database for the UN fuel extends at most up to 14% with different cladded UN fuels.[6] A little work has been done with Nb-1Zr cladding, but the preponderance of available knowledge is with stainless steel cladding. This data base needs to be extended to 25% burnup for both unconstrained as well as constrained UN cermet fuel in order to understand possible failure mechanisms.

The ductile-to-brittle transition temperature is an issue analogous to that for the UO_2 cermet fuels. However, the addition of Re aids in the formability of the matrix material and helps reduce the ductile-to-brittle transition temperature. This issue affects the ability of these fuel elements to undergo cyclic operations in addition to the other effects that transients impose upon the fuel elements.

UN and UO_2 Pin Fuels: The technical feasibility issues for the pin fuels are listed in Table VI.7 for the clad UN and UO_2 fuels. For the UN pin fuels, these issues involve the cladding/UN/fission product compatibility, burnup up to 10% accompanied with the fission product migration and release and fuel swelling, safety margins for transient and off-normal performance, and cycling capability. Performance up to 0.5 kW/cm^3 may be required. For the clad UO_2 fuels used for in-core thermionic devices, the issues involve UO_2 swelling at high temperatures, emitter creep distortion, fission product management and interactions, insulator performance for 10 years, and safety

TABLE VI.6
ISSUES AND REQUIREMENTS FOR UN CERMET FUEL REACTOR DEVELOPMENT--
FUEL DEVELOPMENT AND TESTING NEP

UN CERMET FUEL	ISSUES AND ACTIVITIES

Critical technical issues	UN-W-Re compatibility
	Burnup (up to 25%)
	    Fission product migration and release
	Swelling
	Performance limits
	    Up to 2 kW/cm^3 and 2200K fuel temperature
	    Safety margins for different failure modes
	Cycling capability (DBTT and stresses)
	Coating integrity and stability
	    Ductile-brittle transition temperature
	    Liquid metal compatibility
	Element/element interactions
	    Bowing
	    Failure propagation

Fabrication Issues	Recapture 1986 cermet fabrication technology
	    Fuel coating technology
	    Pressing and sintering
	    Hot isostatic pressing
	Develop UN cryochemical sphere fabrication
	Fuel element characterization
	QA and QC

Crucial Ex-pile Tests	Property measurements and characterizations Compatibility and stability testing Cyclic testing Liquid metal testing Element interaction tests

Irradiation Testing	UN particle irradiation (burnup)
	Cermet sample (burnup and stability)
	Instrumented fuel element tests (7.5 x 68)
	    Statistical tests (reliability)
	    Transient and off-normal tests
	    Safety tests (to failure)

Facilities Requirements	Fuel fabrication and assembly facility Properties and characterization laboratory Instrumented irradiation test loop single element tests Transient reactor Liquid metal testing laboratory Hot cells

TABLE VI.7
ISSUES AND REQUIREMENTS FOR FUEL PIN REACTOR DEVELOPMENT--FUEL DEVELOPMENT AND TESTING

CERMET FUEL	UO_2 PIN (THERMIONIC)	UN PIN (RANKINE)
Critical Technical Issues	Maximum time/temperature capability High-temperature vaporization Liquid metal compatibility Burnup Cycling capability Fission product migration and release Component compatibility Composition stability Element/element interactions	Maximum time/temperature capability High temperature vaporization H_2 and liquid metal compatibility Coating integrity and stability Cycling capability Fission product migration and release Composition compatibility Component compatibility Element/element interactions Burnup
Fabrication Issues	High-temperature emitters Seals Joining QA and QC Characterization Sheath insulators Integral reservoirs	Coating technologies Characterization QA and QC Joining
Crucial Ex-pile Tests	Property measurements Characterizations Cyclic testing Liquid metal compatibility testing Element interaction tests	Property measurements Characterizations Cyclic testing H_2 and liquid metal testing Element interaction tests
Irradiation Testing	Instrumented fuel element tests Fuel pellet irradiation Statistical tests (reliability) Transient and off-normal tests Prototypical assembly tests Safety tests (to failure)	Instrumented fuel element tests Fuel pellet irradiation Statistical tests (reliability) Transient and off-normal tests Prototypical assembly tests Safety tests (to failure)
Facilities Requirements	Fuel fabrication and assembly facility Properties and characterization laboratory Liquid metal testing laboratory Instrumented irradiation test loop for single element tests Transient reactor Hot cells	Fuel fabrication and assembly facility Properties and characterization laboratory Liquid metal loops and test facilities Instrumented irradiation test loop for single element tests Transient reactor Hot cells Hot gas test facilities

margins involving transient and off-normal conditions and fuel pin integrity during launch.

For Nb-1Zr clad nitride fuel pins, the burnup data base extends to about 6% burnup. This data base would have to be extended to 10% burnup for this cladding material, and new data bases developed for 10% burn-up with other claddings that could be used for NEP systems. Requirements for this data base include information on fuel swelling and fission gas retention.

The baseline design for cladded UN pin fuels is found in the SP-100 program. A number of studies have suggested that small extensions of SP-100 concepts could be used in NEP applications. However, as reactor outlet temperatures are increased greater than 1500 K to achieve specific masses less than 10 kg/kW, a number of new issues will need to be considered. At these higher temperatures, compatibility with UN is expected to be an issue with rhenium and other potential cladding materials such as tungsten, molybdenum, or tantalum based alloys. These higher temperatures also impose a substantially higher fuel temperature with cladding creep imposing limits on fuel lifetime. In addition, the higher temperatures may lead to faster reaction rate between the Rhenium driver and the UN fuel. Refractory metals with higher temperature capabilities will have to be selected.

A number of the refractory metals are body-centered cubic materials and exhibit the ductile-to-brittle transition temperature problem. Even at room temperature, these materials can be extremely brittle and are therefore vulnerable to fracture during launch because of the imposed stresses.

The ongoing SP-100 program may produce resolutions to many of these feasibility issues. Higher performance claddings are being evaluated at the NASA Lewis Research Center.

For thermionic devices, one of the principal issues is the tungsten emitter creep distortion. The gap between the emitter and collector critically affects the thermionic performance and must be closely maintained. Fission product release and fuel swelling can impose relatively high stresses on the emitter which can result in creep deformation. If the creep deformation is too large, the thermionic performance is seriously degraded. Advanced emitter materials like single crystal

tungsten/molybdenum alloys and tungsten/hafnium carbide alloys are also being considered to reduce this problem.

Other issues for the UO_2 fueled emitters are fuel swelling and fission gas release. The fuel will be operating at surface temperatures equal to the high (1800 - 2000 K) emitter temperatures, progressively increasing into the center of the fuel. In contrast, the largest data base for UO_2 cladded fuels is from light water reactors (LWRs), which typically have surface temperatures of about 700 to 800 K and centerline temperatures about 2300 K. For thermionic devices, the swelling and fission product release involve extrapolation from the current data base. In addition, if the emitter cracks or the seals break down, fission gas can leak into the gap degrading the thermionic performance.

Because of its high melting point and high work function, tungsten is typically used for the emitter, but it suffers from the ductile-to-brittle transition temperature problem. This behavior presents an issue for the fuel pin integrity during launch. The vibrations and stress could result in fracturing the tungsten emitter, rendering the thermionic device inoperable.

The Thermionic Fuel Element (TFE) program is developing thermionic components such as emitters, insulators, seals, and integral reservoirs. TFE components have been tested in the EBR-II, FFTF and TRIGA reactors. There are also initiatives led by the Air Force and DOE that will produce advanced thermionic concepts and technology development to aid in the resolution of the major issues. One area that needs more effort is the understanding of fuel performance at the high temperatures.

VI.2 <u>FABRICATION ISSUES</u> The previous section and the associated tables presented a brief overview of the principal technical feasibility issues with the fuels. The fabrication development includes the recapture of the NERVA and cermet fuel fabrication technology and incorporating recent advances and requirements into the process. The particle bed fuel development is in progress as part of the Air Force SNTP program. The UO_2 and UN fuel pin development is in progress as part of the thermionics and SP-100 programs respectively. It should be noted that there are a

number of common steps in the development process which can be exploited to speed up the overall development process and reduce cost.

VI.2.1 NTP FUELS

Prismatic Solid Carbide Fuels: The fabrication of the composite fuels involves a similar process to that of the UC_2 dispersed fuel except that spheres will not be required, and hot pressing may be used instead of extrusion and firing. These elements need to be sintered or heated to fuse the carbide "skeleton" of the matrix and to obtain the desired composition. Other than these changes the process is essentially the same.

A graphite fuel extrusion capability was demonstrated at Los Alamos in early 1987. The fuel particle technology was shown to be viable and has been advanced beyond the level achieved in the NERVA program. However, a pilot fabrication line must be assembled: 1) to fabricate tie tube assemblies, 2) to fabricate the element with depleted uranium carbide fuel, and 3) to prepare for fabrication of the geometry-specific element for in-reactor testing.

For the solid solution fuels, new processes need to be developed since bowing during sintering of multi-hole elements was found to be a problem, requiring the carbide fuels to use only one coolant channel in the "spaghetti" fuel form. A process needs to be developed for forming a homogeneous solid solution of metal carbides with uranium carbide. The solid solution feed stock needs to be formed into the desired shape and sintered. Methods need to be developed to characterize the properties of the element and determine the degree of homogeneity.

Initially, small test articles of the composite and solid solution fuels need to be fabricated on a laboratory scale to develop and demonstrate the processes. If testing proves successful for the advanced fuel forms then, a pilot fabrication line will be designed, constructed and used to fabricate the test articles using depleted uranium carbide fuel.

While the pilot fabrication line will be used for preparation of all the fuel for this test plan, early demonstration runs, with depleted uranium carbide fuel, will provide material for out-of-reactor tests.

The task includes the following related specific activities:

a) Redesign (as necessary) and procurement (as necessary) of equipment for a laboratory-scale pilot fabrication line.

b) Installation of the equipment and formulation of material flow sequences.

c) Preparation of material handling and accountability procedures.

d) Identification of equipment reliability and maintenance requirements.

e) Procurement of feed material.

f) Selection of qualified fabrication procedures.

g) Development of nondestructive examination (NDE) procedures to qualify fuel elements for reactor testing.

h) Fabrication of test articles with depleted fuel for laboratory testing.

The process and the pilot fabrication line, described above, will be used to prepare fuel module components and enriched-fuel elements. Dividing the fabrication of depleted fuel and enriched fuel into separate subtasks could result in longer lead times for procurement of the enriched fuel. However, that approach might be necessary from other logistics considerations.

Particle Bed Fuel Elements: Particle bed fuel beads (see Fig. 6-4) have evolved from the TRISO fuels developed for lower temperature HTGR applications. For the Air Force SNTP program, Babcock and Wilcox has produced several batches of the fuel using a process initially developed at ORNL.

The fuel kernels are generally produced using the sol-gel process which results in a dense fuel kernel. As a result, two pyrolytic graphite coatings must retain the gaseous fission products within the particle. A porous pyrolytic layer is deposited adjacent to the fuel in which the porous graphite contains the gaseous fission products. Next is a dense pyrolytic graphite layer that is used as a seal coating to contain the gaseous fission products and to form the substrate for the deposition and formation of the pressure vessel carbide coating. The particle fuel fabricated using the sol-gel process optimizes fuel performance based on design variations such as fuel bead dimensions and materials selection for the fuel kernel and for pressure vessel coatings.

Development of a new cryochemical process was initiated at Los Alamos National Laboratory as an alternative process to the sol-gel process. Initial work with this process indicates that the waste streams can be substantially reduced compared with the sol-gel process because the uranium bearing suspension fluid can be easily recycled by evaporation and condensation. In addition, freeze-dried fuel that does not meet specifications can be easily reintroduced into the freeze drying process without additional processing. The cryochemical process with development of high-temperature fuels appears to be better suited to fuels development for the NTP as opposed to developing fuels that have a high propensity to retain certain fission products or to use graphite coatings.

After conversion to a carbide or nitride, the cryochemical process results in a microsphere that contains substantial porosity compared with the relatively dense microsphere from the sol-gel process (Figure 6-5). The porosity in the fuel can trap the fission gasses and accommodate the pressure generation and swelling from the fission gas release in the fuel. The current activities of the cryochemical process development are directed at identifying the process parameters controlling the particle size and porosity. The fuel porosity negates the need for pyrolytic graphite layers surrounding the fuel kernel since the kernel itself performs this function. Elimination of the graphite coatings offers the opportunity to increase the melting point of the carbide fuel and consequently the operating temperature. Elimination of the graphite coatings increases the liquefaction temperature of uranium carbide fuel since the melting point of uranium dicarbide is 200 K higher than the eutectic temperature of uranium dicarbide with graphite.[7] However, by mixing the uranium carbide with other carbides such as zirconium carbide, the melting point could be increased to 3000 K if graphite is not in contact with the mixed carbides. In the latter stages of development during the ROVER program, some advanced fuels were tested. Composite (U, Zr)C particles coated with ZrC were dispersed in a graphite matrix and tested at 2450 K.[8] Binary carbides containing uranium carbide have been tested in contact with graphite, and the results show that for uranium carbide contents greater than 20 mol/%, the fuel liquifies at temperatures less than 2500 K.[9,10]

To achieve high fuel temperatures and hence high specific impulse, low uranium carbide contents are required, but the paradox is that for high thrust-to-weight ratios or low specific mass for NEP, high uranium loadings are required. For missions meeting both requirements, a compromise has to be reached between maximum fuel temperatures and fuel loadings. However, if high specific impulse is the requirement and thrust to weight is less stringent, low uranium concentration may suffice.

Substantial improvement in the fuel temperatures may be obtained by the addition of niobium carbide to a binary mixture of uranium and zirconium carbides.[1,11] The melting point could be theoretically increased to as high as 3600 K (Figure 6-6). For terrestrial or NEP reactors, this could mean operating temperatures as high as 2080K with the same or lower diffusion rates. Tosdale[1] depended on observing fuel slumping as the indication of fuel melting, but by the time fuel slumping is observed, the temperature of the liquid may have already exceeded the solidus temperature. This potential error may explain the concave slope by Tosdale[1] representing the liquidus rather than the solidus and the concave slope by Brownlee[11] representing the solidus. This increase in melting point needs to be verified by additional melting point determinations.

Because the cryochemical process works with slurries or solid solutions, it is perhaps more amenable for the fabrication of mixed carbides of uranium and zirconium or uranium, zirconium and niobium than the sol-gel process. The sol-gel process would require development of stable colloidal suspensions of solid solutions of the respective mixed oxides. The cryochemical process does not depend to a large extent on a long-term suspension of very fine colloidal particles. If one does not start with a solid solution of the oxides, the solid solution could form during the carbide conversion or subsequent heat treatment.

A protective, external, pressure-vessel coating such as zirconium carbide may still be required for fuel microspheres with uranium carbide, binary carbides, or ternary carbides prepared by the cryochemical process. This coating contains pressure generated by the gaseous fission products and also acts as a buffer separating the uranium carbide mixture from graphite in prismatic fuel structures such as those used in NERVA or separating the uranium carbide from hydrogen and air. The compatibility

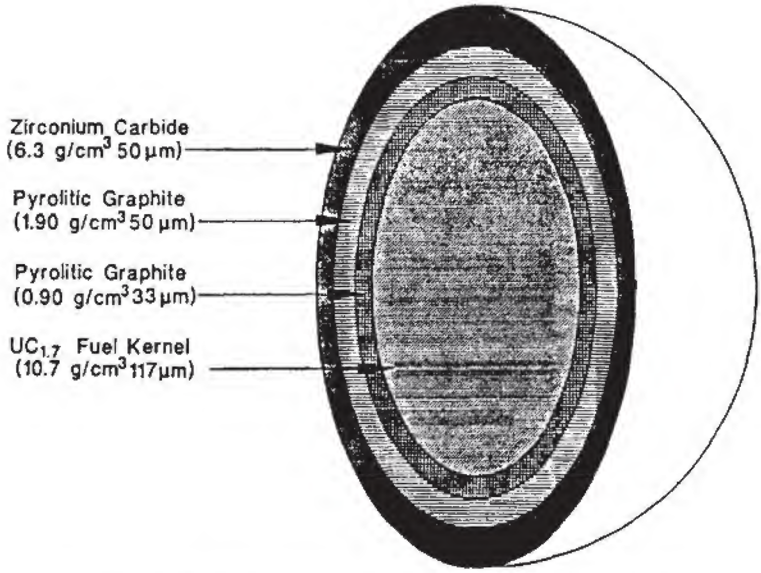

Figure 6-4 Microsphere fuel particle design.

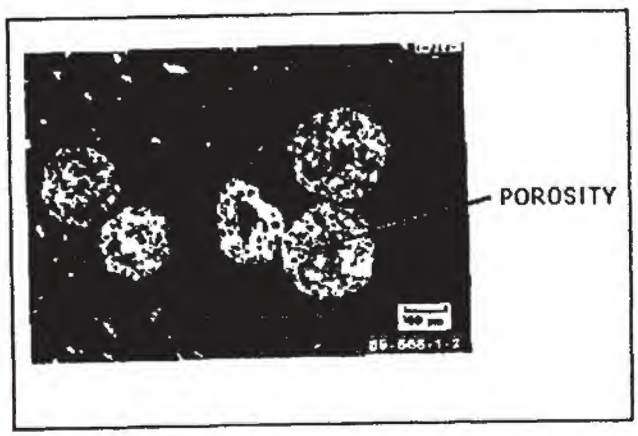

Figure 6-5 Porosity in UN microspheres

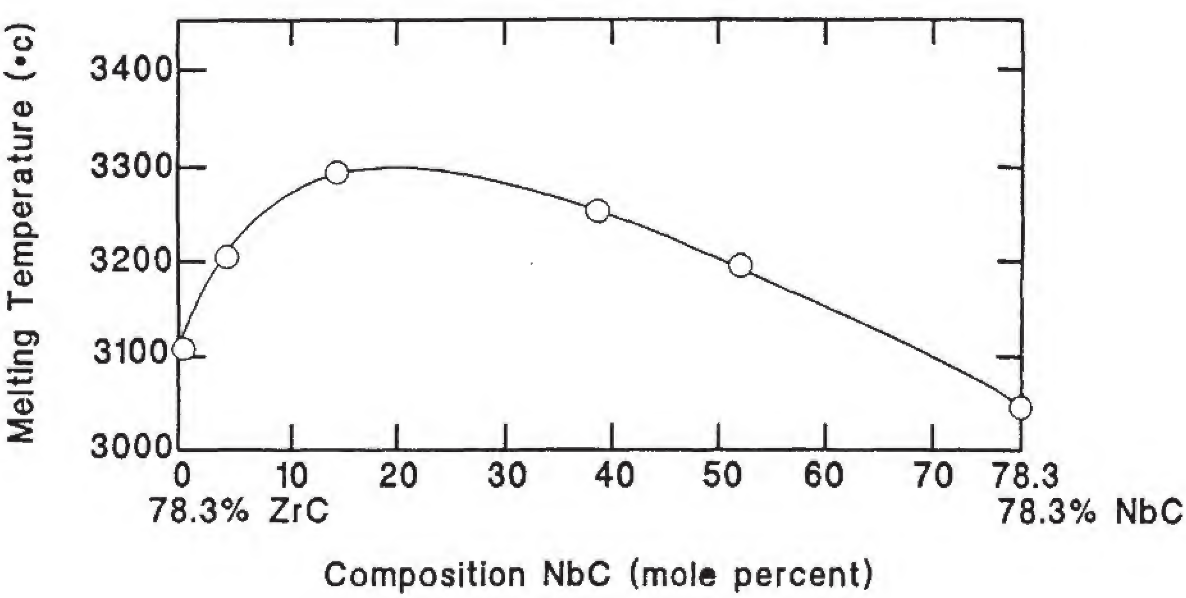

Figure 6-6 Melting point for (U-Zr-Nb)C with 21.7% UC

of this coating with binary or ternary fuels needs to be determined as well as the compatibility with graphite in circumventing any ZrC/graphite eutectic reactions or from hydrogen which severely attacks uranium carbide.

High-temperature materials need to be developed for the hot frits of the particle bed fuel elements. These materials need to operate at temperatures greater than 3000 K and be compatible with the fuels and with hydrogen. Processes will include tube forming techniques such as powder metallurgy and extrusion; and methods to form the coolant channels such as electric discharge machining (EDM), laser drilling and selective etching. Fabrication processes of the cold frit with acceptable thermal-hydraulic characteristics need to be developed. For the Air Force SNTP program several frit materials have been examined and the hot and cold frits have been fabricated and tested.

<u>UO_2 Cermet Fuel</u>: The UO_2 microspheres are electrostatically coated, and these coated particles are blended with the W-Re powder and pressed and sintered into hexagonal blocks. Then the coolant channel surfaces and the external surfaces are cladded with W-Re cladding by hot isostatic pressing (HIPping). Fuel elements were fabricated at ANL using this process during the NERVA program.

The issue is to establish and demonstrate the necessary cermet fuel fabrication technology. A pilot fabrication line will be designed, constructed, and used to fabricate the test articles needed for the planned testing program.

While the pilot fabrication line will be used for preparation of all the fuel for this test plan, early demonstration runs with depleted UO_2 fuel will provide the specimens for out-of-reactor tests.

The fabrication steps include the following activities:

a) Development of a fabrication process,

b) Design and procurement of equipment for a pilot fabrication line,

c) Installation of equipment and formulation of material flow sequences,

d) Preparation of material handling and accountability procedures,

e) Identification of equipment reliability and maintenance requirements,

f) Procurement of feed material,

g) Development of qualified fabrication procedures,

h) Development of nondestructive examinations (NDE) procedures to qualify fuel elements for reactor testing,

i) Fabrication of two or three fuel elements with depleted fuel for process qualification.

The process and the pilot line described above will be used to prepare the cermet fuel elements that contain enriched uranium oxide. Dividing the fabrication of enriched and depleted fuels into separate subtasks permits certification of the process using depleted fuel and provides longer lead times for procurement of the enriched fuel. The fabrication process and coating techniques will be developed for both the cermet fuel block and the fuel particles. A start on this was made in 1986 and 1987 at ANL as part of the multimegawatt space power system program.

VI.2.2 NEP Fuels

Prismatic Solid Carbide Fuels: The fabrication of these fuels has been discussed above under NTP fuels except that the unique requirement for prevention of fission product dispersion into the primary cooling loop is an important requirement for NEP. Although fission product retention was not a primary concern during the ROVER/NERVA programs, future fuel design must address this concern for NEP systems. These fuels need to operate at temperatures around 2000 K to obtain specific power levels less than 10 kg/kW(e) and still retain fission products during the multi-year life of the system.

The fabrication of prismatic carbide fuels begins with the high temperature gas-cooled reactor (HTGR) programs. The fuel used for HTGRs is the TRISO fuel bead, similar to the microsphere described above, except that the peak temperatures for these fuels have been limited to temperatures less than 1300 K. The silicon carbide coating is limited to about 1700 K because of vaporization. Also, the amoeba effect results in deterioration of the silicon carbide coating from the migration of metallic fission products along the temperature gradient. These beads have also demonstrated a capability for 75% burnup, again at temperatures below 1300 K. The other possible carbide coatings (ZrC and NbC) to replace SiC may not be as effective in resisting

penetration of metallic fission products as SiC. The SiC coefficient of thermal expansion (CTE) has a better match with graphite than any of the other carbides under consideration, which is a major factor in the success of the TRISO fuel beads. To reduce the specific mass of an NEP system requires increasing the temperature of the radiator to reduce the radiator area and mass. The higher radiator temperature will require operating the reactor as high a temperature as possible commesurate with safety and reliability. In this sense, the carbon used in the TRISO beads and other fuel forms will have to be eliminated to increase the operating temperatures of the fuels.

An alternative to the classical HTGR fuels is the fabrication of the UC_2 particles dispersed fuel which involves sphere fabrication by the sol-gel process that could be performed by the intergelation process or the external gelation process. Work on the beaded graphite fuels could not be used since the erratic (progressive) corrosion seen in NERVA/Rover fuels tests is not expected with He/Xe inert coolants. The external gelation process was not successful for fabrication of the New Production Reactor (NPR) fuel. A cryochemical process is also being developed at LANL which could be applied to this fuel form. Graphite with a high coefficient of thermal expansion (CTE) needs to be developed. This graphite is needed to match the thermal expansion of the coatings with that of the graphite. The elements are then extruded to form the hexagonal shapes with the coolant channels and fired to convert the organic binder to a graphitic structure. Finally, the surfaces of the elements are coated (inside surfaces of the coolant channels and the external surfaces of the element). Bowing during sintering of multi-hole elements was a problem with the NF-1 carbide fuels. This has implications for between-hole flow transfer in the presence of through cracks that are likely to be present. Initially, niobium carbide was used to coat the graphite surfaces, but later zirconium carbide was used. Although NbC has a better match of thermal expansion with graphite than ZrC, elements were more successfully coated with ZrC than with NbC. This process is a "black art" for which only one out of three vendors, could fabricate fuel elements successfully, and then with four furnaces, only one furnace could produce qualified elements. Most of NERVA fuel fabricators have retired, and a few are working as consultants which make technology recapture extremely difficult.

Particle Bed Fuel Elements: The fabrication of these fuels has been discussed above under NTP fuels. The fabrication of the elements will be similar except for the fissile content which is expected to be much lower than that for the corresponding NTP particle bed elements. The unique requirement for prevention of fission product dispersion into the primary cooling loop is an important requirement for NEP. The cryochemical process for microsphere fabrication offers a potential process for manufacturing porosity in the fuel beads for fission gas retention if impervious, tenacious coatings can be developed. One goal is to fabricate fuel particles without the presence of graphite to prevent eutectic reactions which effectively lowers the melting point of the fuels. These fuels need to operate at temperatures around 2000 K to obtain specific power levels less than 10 kg/kW(e).

UN Cermet Fuel: Stable nitride needs to be developed since this fuel is very reactive with rhenium to form a low density, brittle URe_2[4,5]. Initial scoping tests indicated that this reaction may be controlled through suitable UN stoichiometry. Then the stable uranium nitride needs to be fabricated into microspheres containing some residual porosity for fission product retention. The cryochemical process described above would apply for this fuel. Homogeneous W-Re powders need to be developed. Currently, there is only one source for this powder in the United States, but the homogeneity needs to be verified. The UN microspheres are electrostatically coated, and these coated particles are blended with the W-Re powder and pressed and sintered into hexagonal blocks. Then the coolant channel surfaces and the external surfaces are cladded with W-Re cladding by hot isostatic pressing (HIPping).

The fabricability of the fuel, fuel blocks, and coatings may be dependent on fuel particle stoichiometry, fuel density, matrix composition, fuel-to-matrix ratio, particle size, and coating techniques. It is expected that considerable effort will be needed to explore variations in these parameters to enable consistent production of high quality fuel with a high throughput rate. Iterations on process parameters can be expected on the basis of results from mechanical properties tests.

The necessary cermet fuel fabrication technology is to be established and demonstrated. A pilot fabrication line will be designed, constructed, and used to fabricate the test articles needed for the planned testing program.

While the pilot fabrication line will be used for preparation of all the fuel, early demonstration runs with depleted UN fuel will provide the specimens for out-of-reactor tests.

The fabrication steps include the same activities as described in section VI.2.1 for the UO_2 cermet fuel.

The process and the pilot line described above will be used to prepare the cermet fuel elements that contain enriched uranium nitride. Dividing the fabrication of enriched and depleted fuels into separate subtasks permits certification of the process using depleted fuel and provides longer lead times for procurement of the enriched fuel. Initial work on this has already been started at ANL as part of the MMW program. This subtask includes preparation of fuel elements with optimized particle size, particle fraction, particle density, and coating thickness for in-reactor tests. The fabrication process and coating techniques will be developed for both the cermet fuel block and the fuel particles.

UN and UO_2 Pin Fuels: The fabrication process for assembling these fuels has been fairly well established under the SP-100 program for the UN pin fuels and under the Thermionic Fuel Element development program for the UO2 pin fuels for thermionic applications. However, the material selection and the fabrication process for the thermionic components is still under development under the TFE program.

The fabrication of the SP-100 fuel pins is similar to that for the fabrication of LWR fuel pins. The cladding is in the form of tubes which has a rhenium liner "HIPped" on the inside of the cladding. An end cap is welded to one end of the tubing, and then the UN pellets are inserted into the tube. The last end plug is electron-beam welded to the cladding completing the fuel pin fabrication. The fabrication issues will involve the process development for fabricating advanced cladding materials. The UN fabrication process development has been completed.

VI.3 FUELS TESTING

The objectives of the fuels testing are first discussed followed by a discussion of the flow of information and how the information from the non-nuclear and nuclear testing would be used.

The objectives of the fuels unirradiated and irradiated testing should be to:

1. Provide data to resolve technical feasibility issues;
2. Provide data for design and operating envelope,
3. Provide reliability data,
4. Establish safety margins, and
5. Provide experimental data for code verification and validation.

A number of propulsion system concepts have been proposed and the most promising of these should be developed over the next several years. Before detailed concept development can proceed, the technical feasibility issues will need to be resolved. The fuels development and testing are the means to provide the data for resolving the feasibility issues in the fuels area. In addition to the resolution of the feasibility issues, the irradiated as well as the unirradiated fuels data will provide basic design and operating envelope data upon which the concepts can be further developed and proven.

To support reliability assessment, the mechanisms of different failure modes need to be established such as melting, fuel element embrittlement, or other means of degradation to where the element cannot be used. Failure modes for each type of fuel element would be established, and then a physical model would be established for predicting with temperature and/or time, the point at which failure would occur. These correlations would be developed from ex-pile and in-pile tests.

In conjunction with the reliability data, safety margins and data to support safety analyses need to be established for the fuel. Determination of the safety margins will require determination of the failure modes. For example, for NTP systems because of the very high-temperatures, the safety margin may be 90% of fuel melting or some other fraction of temperature dependent upon the failure mode and of the time for the system to respond to the initiating event with regards to limits that have to be imposed for accident management. For probabilistic risk assessments (PRA),

risk needs to be established from the frequency of failure and the consequences of failure. Both of these factors need to be determined experimentally.

A large part of the experimental data obtained from the fuels development and testing program would be used to validate analytical models. After the codes are verified they need to be validated by comparing the code with experimental data. Verification may be performed by comparing code results with those from other codes known not to have numerical deficiencies.

Most of the codes to be used for experiment and concept analysis are expected to be verified to show that the codes do what they are designed to do. However the codes need to be validated with respect to containing the correct models for phenomena that experimental data shows to occur and the correct equations are used to model the appropriate phenomena. Certain experimental data would be used directly to aid in model development to establish the appropriate constants, but other integral tests would also be used to validate the models.

The recommended flow of fuel fabrication, measurements and testing activities, and the flow of information is depicted in Figure 6-7. The chart begins with the development and fabrication of particle (microsphere) fuels that would be used for the particle bed elements, or feed stock, in the form of oxides or nitrides, for the cermet fuels. Information from the fabrication process for microspheres would be placed into the information data base. The particles (carbides, oxides, and nitrides) would then be used in the capsule testing. As appropriate, the particles themselves or the information on the fabrication of the fuels for the particles would be used in the fabrication of prismatic fuels. These fuels would be either small element segments used for capsule testing or full-sized elements used in single fuel element testing, bundle testing, or reactor/engine testing. Information from the fabrication process should be put into the data base. For particles, fuel element segments, and full-sized elements, these products would undergo fuel characterization to insure the products meet specification and to determine basic physical, mechanical, and thermal properties as required. This information would also be placed into the data base. The fuel element segments and full-sized elements would also undergo non-nuclear testing such as transient heating tests, coolant compatibility tests, and thermal hydraulic tests

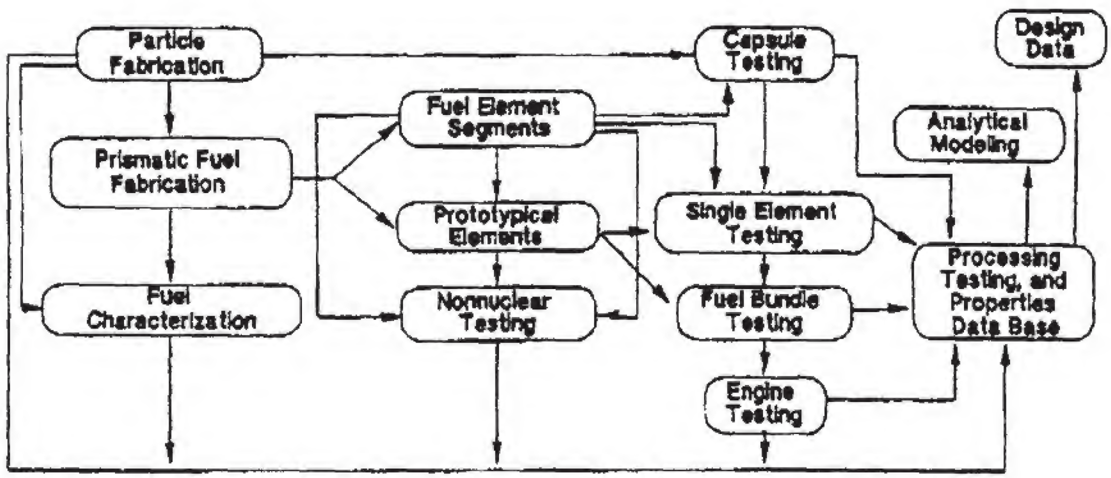

Figure 6-7 Information flow for non-nuclear and nuclear testing

to support the irradiation tests. This information would also be placed into a data base. Test results from the capsule testing, single element testing, bundle testing and engine testing would then be placed into the data base. Information in the data base would contain pedigreed data used for analytical modeling to predict fuels performance and safety analyses, all of which aid in the development of the reactor design.

Detailed development test plan(s) should be developed in concert with the industry led concept to ensure that the test plan adequately reflects the needs for the concept development. The DOE testing laboratory would ensure that the test plan can be executed safely and appropriately for achieving the detailed test objectives.

VI.3.1 EX-PILE TESTING

The ex-pile testing can be categorized into two segments. The first segment is fuels characterization that includes basic physical, mechanical, and chemical properties such as density, melting points, specific heat, thermal conductivity, tensile and compressive strengths, and the chemical compatibility with other materials and the propellants. This characterization also includes fuel design specific data consisting of coating thicknesses, fuel particle and element dimensions, fissile loadings etc. The second segment includes the transient and steady-state non-nuclear tests that are used to support the irradiation testing and the fuels development. These tests would include transient heating tests to determine thermal stresses imposed for start-up and shut down, flow tests with recirculating coolants, and compatibility testing.

Because many of the physical, mechanical, and thermal tests and other non-nuclear tests are common to NTP and NEP fuels in general, descriptions of these tests will not distinguish between NTP and NEP fuels except in those cases where the coolants and temperature ranges are different. The basic physical, mechanical, and thermal tests and measurements that would be required for the carbide, nitride, and oxide fuels are listed in Table VI-8. For the oxide fuels, fuels properties have been thoroughly evaluated and analytical models developed that describe the properties over a wide range of temperatures.[12] Additional effort would be needed to update the properties for any additional work done in the last ten years. For the nitrides, a data base similar to that for the oxide fuels has been developed[13,14], but additional properties need to be added.

Table VI-8

Fuel Physical, Mechanical, and Thermal Properties

Specific Heat Capacity	Ultimate Tensile strength
Thermal Conductivity	Elastic Modulus
Density	Poisson's Ratio
Thermal Expansion	Creep properties
Surface Emissivity	Critical Stress Intensities
Melting points or ranges	Fatigue Properties
Yield stress	Reaction rates with coolants & other materials
Vapor pressure	
Grain Growth rates	Fission product release
	Fission product swelling
Densification	Microstructure & restructuring
Sintering kinetics	Emissivity

There is no existing data base of fuel properties for the carbide fuels so that an extensive effort is needed for these fuels. After a thorough review of the available literature for the carbide fuels, detailed plans can be formulated for the additional property measurements that will be required for the carbide fuels. For non-nuclear tests that are not common, the tests will be described appropriately for NTP and NEP fuels.

The fuels properties data obtained from new measurements as well as those obtained from the literature will be used to develop a fuels properties data base discussed below in the section on Data Analysis.

The other non-nuclear measurements are the fuel characterization measurements required to insure that the fuel meets specifications. These measurements consist of dimensional measurements of the fuel, fuel test samples, and fuel elements. Fissile loadings need to be confirmed by gamma scanning measurements. Fuel and coating composition (including stoichiometry) need to be determined.

The specific non-nuclear testing is discussed by fuel form for nuclear thermal propulsion and nuclear electric propulsion.

VI.3.1.1 NTP NON-NUCLEAR FUELS TESTING

Prismatic Carbide Fuels: For nuclear thermal propulsion, three carbide fuel forms and an oxide cermet fuel are planned to be developed for the first generation fuels. Monary (UC, $UC_{1.7}$, and UC_2) have been used for HTGRs, but because of melting point limitations, these carbides can not be operated at temperatures much above 2500 K. Therefore, for carbide fuels, the emphasis is on the composite fuels, binary, and ternary solid solution fuels for high temperature capability.

The first task would be to determine the phase composition and stability of the binary and ternary carbide fuels. Phase diagrams of the U-Zr-C system and the U-Nb-C systems should be established to validate the earlier work done with these systems and to form a basis for the quaternary phase diagram of U-Zr-Nb-C system done by Brownlee[11] and Tosdale[1]. Other carbide systems such as the HfC-UC and the TaC-UC systems should also be investigated to determine if the high melting points of carbides of tantalum and hafnium raise the melting point of mixtures of these carbides with uranium carbide.

The degradation of the fuels and coating materials should be evaluated by testing these materials in a laboratory-scale, hot hydrogen furnace. The reaction of potential binary and ternary uranium carbide solutions and composite fuels should be determined as well as the potential coating candidates of zirconium, niobium, and tantalum carbides. Specific plans should be developed based upon the deficiencies found in the literature on the compatibility of these materials with hydrogen.

The stability of the composition of the carbides is also of great concern. Data[2] indicate a decrease in stoichiometry with time at relatively high temperatures of carbides heated in vacuum or in hydrogen for relatively short times. This data were for single carbides of zirconium, niobium, hafnium, and uranium. Similar stability concerns exist for the binary carbides and even more important for the ternary carbides. This change in composition affects the melting points of the carbide mixtures.

Particle Bed Fuel Elements: The fuels testing described above for the prismatic solid carbide fuels is applicable for the particle bed fuel elements.

In addition to the tests described above for the prismatic carbide fuels, tests should be conducted to select materials for the hot frits using various candidate hot frit materials, various frit designs, and candidate end-fittings at temperatures and stress levels that are consistent with those expected in service. Laboratory thermal cycling tests should be conducted under prototypic loads and environmental conditions.

Thermal hydraulic flow tests through cold frits for different frit sizes should also be conducted at different temperatures to determine the flow resistance and pressure drops as a function of temperature. Flow mapping of the cold frits used for elements would be required for characterization of these elements. Similar measurements would be required for flow resistance and pressure drops through particle fuel beds to better understand the behavior of particle bed fuel elements and to support those designs that employ fuel bed particle for pressure control. It is noted that the Air Force SNTP program is developing this data and only incremental data needs will be developed under the SEI Program.

UO_2 Cermets: The operating temperature of nearly 2800 K for UO_2 dispersed in a tungsten matrix is challenging to this fuel. At this temperature range the vapor pressure of UO_2 is very high and could lead to the formation of metal uranium in the tungsten matrix. Compatibility testing must be conducted if metallic uranium can form in tungsten over short periods of time and if it results in embrittlement of the tungsten. In earlier ANL and GE work stabilizers such as thoria and gadolinia have been used to solve this problem. Tungsten has been frequently used to contain molten UO_2, and the permeability of oxygen is extremely low when UO_2 and tungsten are both exposed to an inert atmosphere. This behavior needs to be verified for UO_2 contained within a tungsten matrix.

The morphology of the UO_2 at these high temperatures needs to be examined with time and temperature for its ability to contain fission products within the fuel. The effect of vaporization and condensation of the UO_2 in the cermet fuel may affect

fission product release, heat transfer from the particle to the matrix, and the interaction of the fission products with the tungsten-base alloy.

Thermal stress measurements in which the elements can be heated to the highest power densities possible in flowing hydrogen would be required. Because non-nuclear power would be used, the power densities may be limited. However, the temperature gradients may be estimated from normal power conditions, and these may be simulated at lower power densities by lower hydrogen flows. Analysis would be required to verify this approach. This testing is complementary to and not a substitute for irradiation testing because the conditions are not prototypical and the effects of irradiation on materials degradation are not present.

VI.3.1.2 NEP NON-NUCLEAR FUELS TESTING

Prismatic Carbide Fuels: The fuels common to a number of the nuclear electric propulsion concepts are the carbide fuels identified for the prismatic solid carbide fuels and particle bed fuels. The basic differences between these fuels and those for nuclear thermal propulsion are the coolant, operating temperatures, fissile content, power density, burnup and the life times so similar types of non-nuclear testing would be required but at lower temperatures and longer times. However, fuels of this type for NEP have not been well defined. None of these fuels have previously had adequate fission product containment features. Considering the burnup required and the very low fission product release that would be permitted into the primary coolant loop, innovative fuel designs would be required which require testing at temperature and time to screen these fuel designs and fuel fabrication processes.

Particle Bed Fuel Elements: The fuels common to a number of the nuclear electric propulsion concepts are the carbide fuels identified for the prismatic solid carbide fuels and particle bed fuels. The basic differences between these fuels and those for nuclear thermal propulsion are the coolant, operating temperatures, power densities, fissile content, and the life times so similar types of non-nuclear testing would be required but at lower temperatures and longer times with different operating parameters. Considering the burnup required and the very low fission product release

that would be permitted into the primary coolant loop, fuel designs and fuel fabrication processes based on either the sol-gel process or the cryochemical process would require testing at temperature and time to screen these fuel designs and fuel fabrication processes.

UN Cermet Fuels: The nitride cermet fuel element consists of nitride microspheres or particles dispersed in a tungsten-rhenium matrix. Compatibility testing would be required to determine the rate of reaction of UN with rhenium in the W-Re alloy as a function of temperature and UN stoichiometry and doping additions (UN stability). This testing should be done in conjunction with the development of stable UN fuel described below. Testing temperatures would range from 1700 K to 2200 K.

The nitrogen overpressure for stoichiometric UN is extremely high which would lead to the interactions described above. Scoping tests indicate that the extent of the overpressure may be controlled by the stoichiometry of the UN. Doping the UN with very small additions of another nitride may also influence the stability of the UN. Investigations should be performed to evaluate the stability of more stable UN by changing stoichiometry or by doping.

UN and UO_2 Pin Fuels: The testing of both of these type of pin fuels involve testing of different cladding materials for these pin fuels with the respective fuel forms in prototypical geometry. In the case of advanced, higher temperatures UN pin fuels based on the SP-100 design, non-nuclear testing would be required to confirm the kinetic measurements on the creep deformation and the compatibility of the cladding alloys and the barrier materials with the fuels.

Most of the non-nuclear testing for these fuels would involve characterization of the materials described above.

VI.3.2 IRRADIATION TESTING

The irradiation testing should be conducted over several phases. The first phase is based upon testing a large number of small samples for different chemical and physical fuel forms in **capsules** over a wide variety of fuel designs and temperature ranges. These capsule tests would be used to screen fuel designs and provide basic performance data for NTP and NEP fuels and burnup data for NEP fuels. The second phase should consist of **single element tests** using full size elements. These tests would address the feasibility issues, safety margins, performance and operating envelope issues, and to a certain extent reliability issues. The third phase would be **bundle testing** during which various element/element interactions would be determined and the fuel response and thermal hydraulic response to operating and to abnormal transients (such as loss of flow) would be determined. Combination of the above second and third tests into a single bundle test phase using bundle test facilities would also be an acceptable test approach. The final phase should be the **integral engine testing**. These phases are discussed in detail next.

VI.3.2.1 CAPSULE TESTS

Three test capsules are recommended. One capsule should be used to test NTP fuels under temperature conditions representing those for nuclear thermal propulsion. The capsule tests do not need to use hydrogen, but rather an inert gas jacket may be used to obtain the desired fuel temperatures for NTP. Two other capsules are recommended for NEP fuel to represent the temperature and burnup conditions for both the liquid metal cooled reactor using a Li/K-Rankine cycle and a He/Xe cooled reactor using a closed-Brayton cycle. Again, liquid metals do not actually have to be used in these capsules since the temperature control is done by inert gas jackets and the neutron flux levels. Two capsules are needed to manage the longer irradiation times required for NEP.

The capsules would need to be instrumented with thermocouples to monitor the on-line irradiation temperature at various axial locations. Other measurements that need to be made are fission product release, neutron flux, and burnup. Fission product release and burnup would be measured by post-irradications examinations

(PIE) since on-line measurements would be complicated. Neutron flux measurements are performed by gamma scanning of flux wires attached to the capsules.

VI.3.2.1.1 **NTP Samples**

Prismatic Solid Carbide Fuels: Carbide fuels (with different fissile loadings) should be fabricated into wafers that are uncoated and coated with different coating thicknesses of zirconium, niobium, and tantalum carbides. Similarly, pellets should be fabricated using binary solid solution fuels of uranium and zirconium carbide, uranium and niobium carbide, uranium and hafnium carbide, and uranium and tantalum carbide. The composition and fissile loading would vary depending on the optimum compositions determined from the phase diagram. These pellets would be uncoated and coated with either zirconium, niobium, and tantalum carbides of different thicknesses.

Particle Bed Fuels: Carbide fuels should be fabricated into microspheres that are uncoated and coated. Microspheres should be fabricated using binary solid solution fuels of uranium and zirconium carbide, uranium and niobium carbide, uranium and hafnium carbide, and uranium and tantalum carbide. The composition and fissile loading would vary depending on the optimum compositions determined from the phase diagram. These microspheres would be uncoated and coated with either zirconium, niobium, and tantalum carbides of different thicknesses.

UO_2 Cermet Fuels: UO_2 particles and microspheres of different densities would be inserted into their own containers. In addition, these particles would be fabricated into tungsten and tungsten rhenium cermets coated with W-Re cladding. These cermets would be about two centimeters in diameter and one centimeters thick.

Unique fuel samples would contain in their own container or capsule with provision for sampling the capsule gas. The fuel operating temperatures for NTP would range from 2500 K to 3600 K or the fuel melting temperature, whichever is the highest, and for times varying from 10 minutes to 10 hours. Because of the longer irradiation cycles in existing reactors, the initial testing would begin at lower temperatures (between 2000 to 2500 K) for longer times on the order of 30 days. The data at lower temperatures and longer times could then be extrapolated to higher temperatures and shorter times. Eventually, the capsule tests would be culminated in tests for less than 10 hours at temperatures between 2500 and 3600 K or fuel failure which ever is the highest. Because of the complexity in these types of tests with the variations in composition, temperature, types of coatings, coating thicknesses, and flux levels, detailed planning would be based upon a factorial experimental design.

Capsule tests should also be performed to determine the retention of fission products as a function of temperature and fuel design and to determine the integrity of the fuel under irradiation and high temperature conditions. Data from these tests would be used to evaluate fuel designs and validate non-nuclear testing for coating compatibilities and fuel stability.

Samples for burnup, fission product retention, and carbide microstructure and phase content should be obtained. Coatings would be examined for any spallation or diffusion into the fuel. Some duplicate samples would be required of the low-temperature irradiated samples since some of these samples could be used for high-temperature irradiations.

Recommended post irradiation examinations (PIE) for the capsules should include visual/photographic examinations to record the visual appearance of the samples, dimensional measurements to record swelling in the samples, and immersion density measurements to determine any changes in density. For those samples to be examined by optical metallography and by scanning electron microscopy (SEM), they would be autoradiographed to determine distribution of fission products in the sample.

Samples should also be obtained to determine fission products by inductively coupled plasma spectrometry (ICP) and by chemical analyses.

The fuel would be irradiated for 1 month, the fuel train removed and another fuel train inserted for another month. This process would be repeated until three trains have been irradiated for fuels of a particular fuel form (Figure 6-8). In addition to the on-line tests, fuel samples would be removed periodically after one-month irradiations and would be examined to determine degradation in the fuel and stability of the coatings. The axial flux variation in the test train should result in a number of different samples subjected to different neutron flux levels and hence power levels with corresponding different temperatures. The small samples could be withdrawn at various times in order to build up an exposure history of temperature and power levels.

A minimum flux of 1×10^{14} n/cm^2/s would be required in order to approach the power densities of 5 MW/ℓ and the desired temperature ranges. Lower power densities for these screening tests would be acceptable since the main emphasis should be on the operating temperatures and fuel performance for these atypical samples.

VI.3.2.1.2 **NEP Samples**

Prismatic Solid and Particle Bed Carbide Fuels - The NEP samples would be essentially the same as those fabricated for the NTP fuels except that the fissile content is lower because of the lower power densities required for NEP systems.

UN Cermet Fuels - UN particles and microspheres of different densities would be inserted into their own containers. In addition, these particles would be fabricated into tungsten/rhenium cermets coated with W-Re cladding.

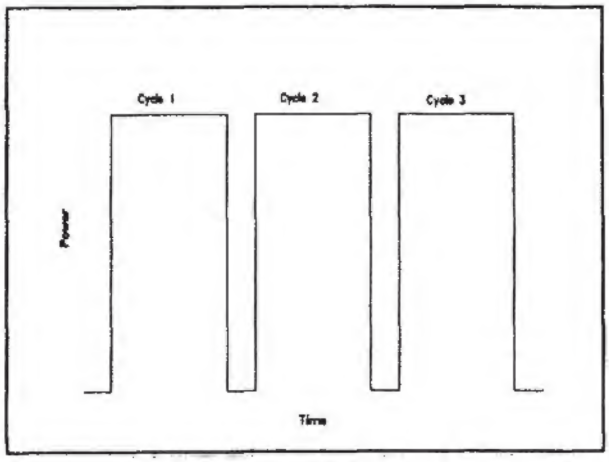

Figure 6-8 Capsule irradiation history

Unique fuel samples would be contained in their own container or capsule with provision for sampling the capsule gas. Each container would be placed in a capsule holder with a flux wire attached to the holder. Fuel tests would be conducted for a accumulation of burnup over a range of temperatures between 1500 and 2200 K for the Rankine system and between 1400 K to 2100 K for the closed Brayton cycle and for times varying from one month to 48 months or until the maximum burnup is attained. The NEP capsule tests would complement the NTP capsule tests by providing data at lower temperatures but longer times that may aid in extrapolation of the NTP performance to higher, but untested, temperatures. As before, the complexity in these types of tests with the variations in composition, temperature, types of coatings, coating thicknesses, and flux levels, would dictate the use of a factorial experimental design.

Capsule tests would be performed to determine the retention of fission products as a function of temperature, burnup, and fuel design. In addition, fuel performance, such as fuel swelling, would need to be determined as a

function of temperature and burnup. The post irradiation examinations for the capsules would be similar to those described in section VI.3.2.1.1. for the NTP samples.

A minimum flux of 1 x 10^{14} n/cm^2/s would be required in order to obtain required burnups in a relatively short period providing that there is not an effect of flux level on fuel performance. A lower flux level may be used with corresponding longer irradiation times. Two capsules are anticipated for the closed Brayton and the Rankine systems to handle the longer radiation times although the typical coolants would not be used in these capsules.

The fuel would be irradiated for 6 months, the fuel train removed and another fuel train inserted for another six months. This process would be repeated until three trains have been irradiated. This cycle woud be similar to that for the NTP capsule irradiation depicted in Figure 6-8 except for the test duration before sample removal. In addition to the on-line tests, fuel samples would be removed periodically and would be examined to determine any degradation in the fuel and stability of the coatings. Samples for burnup, fission product retention, and fuel microstructure and phase content would also be obtained. Coatings would be examined for any spallation or diffusion into the fuel or matrix material.

VI.3.2.2 FUEL ELEMENT TESTS

For each series of tests with a given element, pre-test predictions would be performed to predict the thermal/hydraulic and fuel element behavior for normal and abnormal conditions. These predictions would be used in safety analyses of the tests and to identify any potential safety or environmental issues. To the best of the state-of-the-art technology, the codes or models used for these analyses would be verified codes, that may not be completely validated. Some benchmarking would be required to down select existing codes for their potential applicability to the testing. Proposed requirements for these codes and models are discussed below under Data Analysis.

For estimating purposes, twelve NTP elements of each type are recommended to be tested in order to resolve feasibility issues, establish safety margins, assess reliability, provide performance data, and provide data for code validation. Nine NEP elements of each type are assumed to be tested over an eighteen month period of testing for each type element. These estimates of the number of elements to be tested require additional analysis and evaluation to insure that the required number of elements would provide the needed information within the uncertainties required.

VI.3.2.2.1 **NTP Fuel Elements**

Prismatic Solid Carbide Fuels - Hexagonal shaped elements of the composite fuels and solid solution fuels would be fabricated with approximate prototypic dimensions. Presently, the projected length is 100 cm, but could be shorter to conserve fuel, pending analysis of the effects of the length effects on the axial power distribution and the thermal hydraulics. Shorter elements may be used, but the cross sections would be full sized to reflect the radial temperature gradients. Fuel elements would be fabricated from composite carbide fuels and coated with a carbide selected from previous non-nuclear and capsule testing. Similarly, fuel elements would be fabricated from binary or ternary solid solution fuels selected on the basis of the non-nuclear and capsule irradiations. The composition and fissile loading would vary depending on the optimum compositions determined from the phase diagram. These fuel elements would be coated with a carbide coating.

Particle Bed Fuel Element Particle bed elements should be fabricated using stainless steel, aluminum, or some other appropriate material for the cold frits. The hot frits to be determined from the non-nuclear testing and development activities may be based on a carbon-carbon composite with a carbide coating or may be fabricated from a carbide such as zirconium or niobium carbide. The fuel would be placed in the annulus between the two frits. The composition of the fuel should be selected using the results of the non-nuclear and capsule testing. The length of these elements would be as near prototypic as possible.

Design changes to be evaluated may include frit configurations (materials or pore structure) fuel particle packing fractions, and end-hardware designs. In-reactor testing is important to the PBR concept because many of the issues are associated with the interaction of the fuel, fuel bed, and frit. The temperatures and temperature gradients that influence these interactions cannot be adequately simulated out-of-reactor.

UO_2 Cermet Fuels - Full size elements would be fabricated with 37 coolant channels. These elements would contain 60 vol/o UO_2 in a tungsten matrix. Similarly to the carbide fuels discussed above, analysis would be required to determine if the full fuel length is required.

In this report, it is proposed that in-reactor testing be used to investigate fuel element behavior failure modes, safety margins, and failure frequency. Modifying a typical test reactor to operate with hydrogen loops is expected to be a difficult task to achieve. Significant radiation effects and other issues are expected and would need to be resolved. Constructing and operating a completely new bundle test reactor facility may be the simplest approach. The Facilities Panel Report[15] should be referred to for further details concerning test facilities and test approaches.

The assumed test matrix includes combinations of power densities less than 5 kW/cm^3, temperatures between 2500 and 3600 K, and times ranging from 10 minutes to 4.5 hours. Fuel element performance would be used to determine the operating envelope defined by the design operating power and temperature as a function of time without the temperature exceeding the specified design limit. Failure points and rates (mechanisms of fuel failure) would be determined at power levels, times, and temperatures above the operating envelope. The assumed safety margin is the difference between the operating envelope and fuel failure. An experiment factorial design should be developed in conjunction with pre-test predictions to obtain the maximum amount of information with the smallest number of samples, but the testing could reflect a combination of the power/time histories depicted in Figures 6-9 and 6-10.

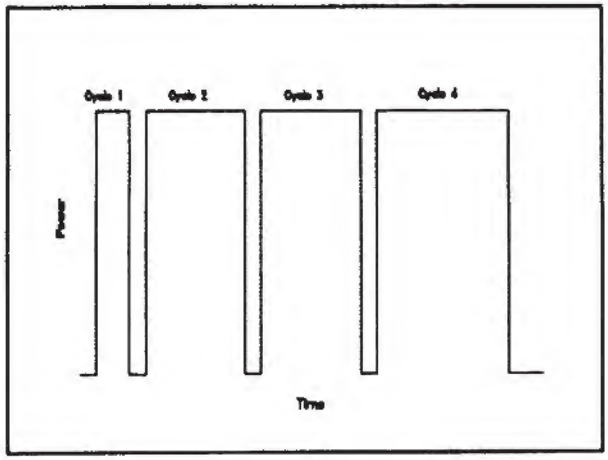

Figure 6-9 Increasing time at constant power

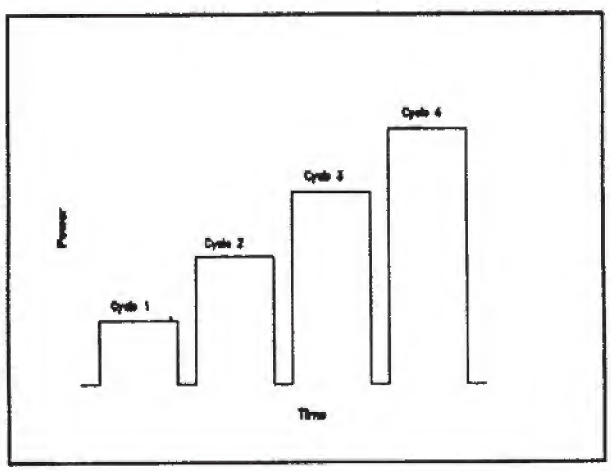

Figure 6-10 Increasing power at constant time

The figures depict one reasonable way of tackling the fuel testing problem. A number of samples could be tested in the manner shown in Fig. 6-9 whereby increasing irradiation times are used at a given power level and temperature condition. The process would be continued until the goal lifetime is achieved or until fuel failure is observed via fission product release in the coolant. A test design matrix could be developed that would provide fuel lifetime data at various power levels and temperatures.

In order to determine an operating envelope, an approach such as shown in Fig. 6-10 could be used. Power could be increased in sequential tests for the same irradiation times. By maintaining the same coolant flow rate the temperatures could be altered and the behavior of the fuels at operating temperatures and beyond could be observed. These and similar approaches could be used to develop the required normal operational and off-normal condition data on fuel and also identify the progression toward failure. These data would be of help in fuel element and core design as well as in setting operational limits.

Single element tests have been suggested for each type of fuel (prismatic carbide, UO_2 cermet, and particle bed element) to measure the fuel element performance as a function of temperature, flow rates, and potential operating scenarios. These tests would address the feasibility issues for each reactor type such as compatibility with hydrogen, power/flow matching, safety margins, cyclic operation etc. Ultimately, the last elements would be tested to failure to determine the failure modes for the different elements required for safety, probabilistic risk assessments (PRA), and reliability determinations. Tests would be repeated with different elements to validate reproducibility. A number of elements are expected to be tested to demonstrate performance, reliability, and determine safety margins.

The instrumentation required for the loop would consist of thermocouples appropriated positioned at the inlet of the element, along the length of the element and at the exit to determine the inlet hydrogen gas temperatures, temperature measurements at different axial positions along the fuel element, and the exit gas temperatures. For the very high NTP temperatures, development of temperature detectors (thermocouples or non-contact devices) would be required. Flow and pressure measurements would be made for the hydrogen coolant including pressure

drop measurements across the element. Self-powered-neutron-detectors (SPNDs) would be used to monitor the power in the fuel element. The temperature rise of the hydrogen coolant and the flow rate would be used to check the power level in the fuel element.

The post irradiation examinations for the NTP elements are similar to those described in section VI.3.2.1.1. for the NTP capsules.

A minimum flux of 1×10^{14} n/cm^2/s would be required to obtain required power densities from 2 to 5 kw/cm^3 in the fuel. This flux level is based upon a thermal spectrum, but detailed analyses would be required to better determine the required flux level taking into account the effects of the spectrum on the fission cross sections.

Each element would be in the reactor for a month although it would not necessarily be in the neutron flux all the while. After the test, the fuel would be removed and another fuel element inserted. This process would be repeated until all fuel elements have been irradiated. After testing the fuel elements would be visually inspected and undergo post irradiation examinations.

VI.3.3.2.2 **NEP Fuel Elements**

Prismatic Solid Carbide Samples - NEP fuel elements would be essentially the same as those fabricated for the NTP testing. The fissile contents may be lower because of the lower power densities. Although other fuel designs such as those for the relatively low temperature gas cooled reactors could be used, these fuels were generally limited to about 1300 K and may not give the performance and reliability required for NEP reactors.

Particle Bed Fuel Elements Particle bed elements would be fabricated using stainless steel, aluminum, or other appropriate materials for the cold frits. The hot frit materials to be determined from the non-nuclear testing and development activities may be based on refractory metals since these elements operate at lower temperatures than the corresponding elements for NTP. The NTP testing would complement the NEP testing from extrapolating the high

temperature performance to lower temperatures. The NTP hot frits still may be required for high reliability for the long NEP lifetimes. The composition of the fuel would be selected using the results of the non-nuclear and capsule testing. Design changes to be evaluated are similar to those discussed in section VI.3.2.2.1. for the NTP particle bed fuel elements.

UN Cermet Fuels - Full size elements would be fabricated with the appropriate number of coolant channels. These elements would contain 56 vol/% UN in a tungsten-rhenium matrix. Analysis would be required to determine if the full length is required similar to the carbide fuels discussed above.

In-reactor testing would be used to investigate fuel element behavior. The test matrix would include combinations of power densities less than 0.5 kW/cm^3, temperatures between 1400 and 2100 K for closed-Brayton cycle, and between 1500 K and 2200 K for the liquid metal Rankine system. Different fuel elements described above would be used in the same closed Brayton loop. The test train would be designed to interface with the test facility and the fuel elements to be tested. Flow rates would vary to obtain the desired temperatures in the fuel elements for different power levels.

Single element tests have been suggested for each type of fuel (prismatic carbide, particle bed element, UN cermet) to measure the fuel element performance as a function of temperature, flow rates, and potential operating scenarios. These tests would address the feasibility issues for each reactor type such as compatibility with hydrogen, power/flow matching, safety margins, cyclic operation etc.. Ultimately, the last elements would be tested to failure to determine the failure modes for the different elements required for safety, probabilistic risk assessments (PRA), and reliability determinations. Nine elements are anticipated to be tested to demonstrate performance, reliability, and determine safety margins.

The instrumentation required for the loop would consist of thermocouples positioned at the inlet of the element, along the length of the element and at the exit to determine the inlet gas temperature or liquid metal temperature respectively for the closed Brayton and Rankine systems, the exit coolant temperatures, and temperature

measurements at different axial positions along the fuel element. Flow and pressure measurements would be made for the coolant including pressure drop measurements across the element. Self-powered-neutron-detectors (SPNDs) would be used to monitor the power in the fuel element. The temperature rise of the coolant and the flow rate would be used to check the power level in the fuel element.

The post irradiation examinations for the fuel elements would include visual/photographic examinations to record the visual appearance of the elements, dimensional measurements to record deformation, and immersion density measurements of the fuel at different axial locations to determine any changes in fuel densities. For those samples to be examined by optical metallography and by scanning electron microscopy (SEM), they would be autographed to determine distribution of fission products in the fuels. Samples would be obtained to determine fission products by inductively coupled plasma spectrometry (ICP) and by chemical analyses for I-129, Sr-90, and tellurium. Neutron activation would be used to determine the fissile content in the fuel.

A minimum flux of $1 \times 10^{14}\ n/cm^2/s$ would be required to obtain required power densities in the fuel. Eighteen month irradiations have been assumed to achieve the required burnups. This flux level is based upon a thermal spectrum, but detailed analyses would be required to better determine the required flux level taking into account the effects of the spectrum on the fission cross sections. As part of this analysis, appropriate flux levels would need to be determined for expediting the irradiation times. A concern will be the effect of higher burnup rates on the fuel behavior.

Fuel properties of the irradiated elements and materials would be determined for those properties identified under non-nuclear testing. Irradiation is known to change the thermal, physical, and mechanical properties of the fuels. For example, irradiation of UO_2 is known to increase the creep rate by orders of magnitude. The appropriate measurements required would be selected from the development of the data base described under Data Analysis.

Each element would be in the reactor for six months before the elements are removed for examination although it would not be in the neutron flux all the while.

After the test, the fuel would be removed and another fuel element inserted. This process would be repeated until nine fuel elements have been irradiated. After testing, the fuel elements would be visually inspected and undergo post irradiation examinations.

VI.3.3 BUNDLE TESTS

The bundle tests would be performed to determine the element/element interactions arising from such situations as loss of coolant, improper orificing, loss of pumps, etc. A bundle test facility could also accomplish the single element tests if desired. These types of tests would not only emphasize performance qualification but also safety qualification in determining the consequences and identifying potential design basis accidents. Concept development needs to move further ahead, analytical tools need to be verified and validated before detailed experiment requirements can be established. Because of the statistics involved with testing a large number of elements, bundle tests can yield the largest data base on fuel qualification from a performance and safety point of view. The qualification criteria would need to be developed. These requirements depend on concept development and available analytical tools. Preliminary requirements based on single elements are listed under the Bundle Test Facilities.

VI.3.4 ENGINE TESTS

The engine tests represent the transition from fuel development to the systems development. Details of these tests will be developed later in the program.

VI.3.5 DATA ANALYSIS

Analytical models in the form of computer codes or smaller modules will be needed to assist in developing detailed test plans, analyzing test results, performing pre-test as well as post-test predictions, and modeling fuel element and reactor performance. The analytical models required for these analyses are not readily available because most of the modeling has been done for Light Water Reactors (LWRs) using incompressible coolants and different fuels and fuel element designs

than those proposed for nuclear propulsion. However, a number of models and codes do exist that were developed for light water reactors which may be applicable to space nuclear systems. Benchmarking of these codes will be needed to determine deficiencies and whether the codes can be modified or new codes developed. Existing computer models already written in FORTRAN must be programmed in FORTRAN 77. The preference for any new code is "C" or" C++" programming language. This language is more versatile and ought to run faster than FORTRAN 77 programming language. No extensions are permissible in order to allow portability among different computer and operating systems.

Since most of any of the fuels related models require material properties, requirements for modeling the materials physical, chemical, and thermal properties are described next.

The appropriate materials property data listed above under laboratory testing, both literature and new data generated from unirradiated test and irradiated capsule and element tests should be reviewed and evaluated. The data must be pedigreed, that is, well-characterized with fabrication history and impurities identified. All the data selected from the review and evaluation should be fit to theoretical models (equations) that would describe the materials under the appropriate temperature and stress conditions. If theoretical models are not available, empirical fits would be used.

Of the three chemical forms of the fuel, substantial effort has been put forth in assembling and assessing the data for material properties data base for the nitride and oxide fuels[12-14]. A data base has been assembled for the oxide fuels in support of the light-water reactors and the Severe Fuel Damage (SFD) programs for the Nuclear Regulatory Commission (NRC). The oxide data base is a compilation of the world's data on UO_2 and mixed oxides of UO_2 and PuO_2. The data have been evaluated and assessed for their accuracy and consistency. FORTRAN programs were developed from this data for use in thermal and mechanical codes to predict the behavior of the oxide fuel. This data base has been used world wide in assessing LWR fuels. Two data bases for the nitride fuels; one developed for the SP-100 program[13] and the other one developed by Texas A&M University[9]. The nitride data base by Texas A&M was patterned after the oxide data base. These data bases establish the need

for additional information and the testing that will be required to obtain that data. The data for the carbide fuels have not been assembled and evaluated in a consistent and thorough manner as that done for the oxide and nitride fuels. There is substantial data available for the high-temperature gas reactors (HTGRs) at temperatures less than 1300 K but needs to be assembled. The development of a data base for the carbide fuels should be initiated.

Irradiation data on the different fuel forms as well as the fuels properties would be maintained in a data base. These data would include the fuel type, the irradiation facility, power levels, burnup, irradiation temperatures etc.

The analytical tools discussed in this plan are those required to conduct the fuels development and testing. It is not the intent to set requirements for other codes not necessary to fuels development such as mission codes. The codes discussed here may not be limited to only fuels testing but may also be applicable to engine or reactor concepts. The types of codes required are system codes that describe the thermal/hydraulic response of a system to operating as well as abnormal conditions, neutronic codes to predict power levels and reactivity worth etc., fuel element codes that describe the thermal, chemical, and mechanical response of fuel elements also to normal and abnormal conditions, and finally fission product models that describe the inventory and release of fission products from the fuel elements. These latter models could also be a part of the fuel element codes.

The thermal/hydraulic codes would be used to analyze as a system, single element and bundle tests. These codes need to incorporate hydrogen and possible other potential coolants such as ammonia, carbon dioxide, and water. These codes need to be able to accommodate compressible coolants. Other models need to be included for modeling various components such as pumps, valves etc. The thermal/hydraulics also need to incorporate heat transfer between the coolant and the walls of the piping and other structures. Although the details of the nuclear power supply would not necessarily be required, these codes need to incorporate a heat source for a more generic engine code.

Neutronic codes are required to predict power levels in the test fuels, reactivity worth of the elements and control rod material for experimental support and safety

analyses. These codes need to have three dimensional capability and contain the relevant neutron cross section libraries for thermal, epithermal, and fast spectrums. More than one neutronic code may be required to complete the neutronic analysis.

The fuel element codes would complement the thermal hydraulic codes discussed above. These codes would model the details of the thermal, mechanical, and chemical behavior of the elements under normal and transient conditions. Although a single code is not necessary to model different fuel forms, separate codes may be used to model each type of fuel element. The preference is to have one code that can handle different fuel element geometries.

Fission product inventory and release codes will be required to determine the fission product source term. These codes are intended to be related to fuel elements and need to incorporate fission product release rates in order to produce a realistic prediction of the inventory. Based upon the fission product inventory these codes need to be able to predict decay heat.

A number of codes have been developed for light water reactors fueled with zircaloy cladded UO_2 fuel pins and are based on a large experimental data base. Most of these codes with appropriate modifications could be applied to space nuclear power and propulsion. Since large financial investment has already been made in developing these codes, advantage needs to be taken to use these codes with appropriate modification for reducing the cost of code development and shorten the time of development to have these analytical tools available in a timely manner. Therefore the primary emphasis for code development for fuels development is to modify existing codes. Modification of the existing codes will include upgrading the programming language to be equivalent to FORTRAN 77 if they are already written in FORTRAN. These codes need to be screened to determine whether they are or could be applicable to space nuclear power and propulsion fuels.

Potential codes and models that potentially may be used are identified below. Other codes may be available so that some benchmarking will be required and an evaluation to select those codes for further development at the lowest cost.

<u>ATHENA or COMIX</u> - thermal/hydraulic codes for system analyses.

<u>MCNP Monte Carlo</u> - neutronic code for predicting power levels in three dimensions.

<u>FRAP-T6 & FRAPCON</u> - Fuel Rod Analysis Codes for steady-state and transient analyses of pin fuels.

<u>TECMDL</u> - Thermionic performance code for pin thermionic elements. This code could be incorporated into other thermal, mechanical, and chemical fuel element codes to improve the analysis for performance and lifetime.

<u>ORIGEN-2</u> - Fission product inventory.

<u>FASTGRASS</u> - Fission product release code.

VI.3.6 FUEL DISPOSAL

The irradiated fuel elements would likely be disposed by reprocessing the fuel rather than storing the fuel in long-term storage. Although storage may be economically cheaper than reprocessing, irradiated fuel storage for millions of years will not be acceptable by the public and the availability of the Yucca Mountain high-enriched uranium storage is uncertain. In the interim, the fuel may be stored for short times until sufficient quantities of irradiated fuel that make reprocessing economically feasible. Carbide fuels from the ROVER and NERVA programs had been previously reprocessed, but the facilities no longer exist. The hope is to reprocess the fuels to remove the actinides and the fission products and then burn the actinides in a suitable reactor to produce fission products with total life-times of less than 300 years. The Integral Fast Reactor (IFR), currently under development at Argonne National Laboratory, could demonstrate the feasibility of this approach in the next several years. The advanced fuels for oxide in TFEs, cermets, nitride, and carbide fuels will require substantial process development.

VI.4 FACILITIES

The Facilities Panel Report[15] present detailed descriptions of recommended test approaches and the required test facilities. A brief overview of facilities is included here for completeness.

VI.4.1. Laboratory Facilities

To perform the basic fuels property measurements, a laboratory equipped with material properties measurement equipment will be required. Carbide and nitride fuels need to be protected from the air atmosphere, at least, until they are coated or encapsulated as appropriate. For this reason, equipment needs to be installed in atmosphere-controlled glove boxes. A facility to hold several glove boxes will be required for the various measurement equipment. The measurement equipment that will be required is listed below.

Density - Density is affected by the material composition (i.e. the fissile content and the matrix materials) as well as the porosity in the fuel. Density can be determined very simply through immersion techniques by the displacement of an appropriate liquid of known density at a given temperature. The open porosity can be also determined by this technique. In support of the density measurements, the pore size distribution is also required to determine the propensity of the fuel to density during normal operation. A mercury porosimeter is used to determine this distribution by measuring the volume displaced as a function of pressure.

Specific Heat - Specific heats or enthalpy of fuels are determined from calorimetry. The essence of these measurements is to heat a specimen to a desired temperature, and then drop the specimen into a liquid of known heat capacity. The temperature rise of the liquid is measured, and from the temperature rise and the known heat capacity of the standard liquid, the heat capacity of the specimen is determined. Specific heat capacity is determined from the slope of the heat capacity versus temperature curve.

Thermal Conductivity - Thermal conductivity is generally determined from measurements of the thermal diffusivity and specific heat capacity as a function of temperature, although direct thermal conductivity measurements could be made from measurements of the temperature gradient and the thermal flux, or in turn the power generation. However, the latter measurements are more difficult to perform and suffer from the largest errors. Two techniques

exist for measuring thermal diffusivity. The first is based on a flash method in which a sample is heated on one side by a pulse of energy, and the temperature rise is measured on the opposite side, and the second is a phase shift method in which oscillating power heats one side of the sample and the phase shift of the temperature oscillation with the power is measured on the opposite side of the sample.

Both diffusivity techniques allow the samples to be encapsulated for the protection of the samples from the environment and containment of vapor pressure or liquid samples. The thermal conductivity of the encapsulating materials as well as the thermal losses have to be accounted for in the temperature rise measurements or in the phase shift measurements. Analytical solutions have been developed based on assumptions of adiabatic heating with no heat losses. Numerical techniques free the solutions from such assumptions.

Mechanical Properties - Mechanical properties include measurements of the tensile strength, compressive strength, Poisson's ratio, elastic modulus, fatigue properties, and the creep or stress rupture properties. The mechanical property measurements are important in determining the load bearing capabilities of the fuel and its ability to resist thermal shock once the temperature gradients have been established by measurement or by analytical means.

The tensile and compressive strengths are determined by standard mechanical testing procedures established by the ASTM (American Standards for Testing and Materials) and require tensile testing machines with appropriate furnaces and atmosphere control equipment. Creep measurements are performed using creep frames that contain the mechanical equipment for loading the specimens at constant stress rather than constant load. The sample strains are determined from changes in sample dimensions that are recorded as a function of time. Elastic modulus are determined from longitudinal and shear waves generated in samples of precisely known dimensions. Of course, all the

mechanical property measurements are affected by the porosity in the fuel that also needs to be determined by mercury porosimeter measurements discussed above.

Chemical Compatibility and Stability - Details of these measurements are discussed with each fuel form, and only the general approach is presented here. The equipment required for these measurements is straight forward. A furnace or several furnaces are required that can operate over the desired temperature ranges with the appropriate temperature and atmosphere control. The furnaces require at least a 5 cm uniform temperature zone for temperature control of the sample. This equipment will be used to heat samples isothermally at various temperatures for different lengths of times and from the measurements of weight or thickness measurements of the reaction products, reaction kinetics can be determined.

A bench-top, hot hydrogen laboratory will be required to determine the compatibility of various materials in hydrogen. This equipment would be a laboratory scale to measure corrosion or erosion rates as a function of temperature, time, and flow rates. Although flow rates through a full-sized fuel element could be as much as 0.1 lb/s, the flow rates in this laboratory fixture is very low, sufficient flow to not starve the reaction of the fuel or coatings with hydrogen.

VI.4.2 Fuel Fabrication Facilities

Fuel and fuel element fabrication that will be needed for testing would be done initially on a laboratory scale since the number of elements per fuel form would be small and several different fuel forms with different designs will be required which results in fuels with different one-of-a-kind designs.

Fuel fabrication facilities would be required for fabricating fuel elements for each reactor concept. When sufficient experimentation has been completed to resolve feasibility issues and preliminary concept development has been completed, fuel

fabrication facilities would be required to produce an estimated 600 to 800 kg of enriched (93%) uranium per year. It is anticipated that NTP and NEP would be pursued in parallel, but because of anticipated funding limitations, the fuels development would likely be an evolutionary process rather than a down-selection process. Therefore these facilities should be flexible in accommodating newer, advanced fuels as these fuels are developed.

These facilities also should have to have extensive inert controlled atmospheres since the fuel forms are most likely to be nitride or carbide. Since the fissile material would be enriched to concentrations greater than 20% U-235, appropriate special nuclear material safeguards will have to be in place such as double fences with motion detectors and appropriate security personal and fuel faults. This facility would need to have the appropriate licenses for handling hundreds of kilograms of fissile material with greater than 20% enrichment. The fabrication equipment should be as autonomous as possible in order to keep personnel exposures within ALARA limits.

VI.4.3 **Irradiation Facilities**

An overview of NTP and NEP irradiation facilities is presented next. Following the earlier discussion on classes of irradiation tests required, facilities would be needed for capsule testing, single element testing, under near prototypical conditions and bundle testing. The final step of engine testing would be performed in a special engine test facility. Detailed discussions on the facilities are presented in Ref. 15; only a brief overview is presented here for completeness.

The strategy is for the capsule testing to be performed in existing facilities. For single element testing for NTP and NEP, an existing facility may be used in place of constructing a new facility. Because of the relatively high power levels required for NTP, a facility for testing bundles or clusters of elements will also be required. If configured appropriately, a new facility could handle both single element and bundle testing for NTP. A facility for testing bundles of NEP elements will not be required since a prototypical reactor will suffice for this type of testing.

After appropriate capsule and element bundle testing for NTP and NEP, facilities for ground testing need to be available for NTP engine testing and for NEP reactor

testing. The NEP reactor and power conversion equipment would also be tested separately from the thruster. These facilities would meet applicable Federal, State, and local codes and environmental and safety requirements. Detailed technical requirements are to be determined (TBD) after further concept definition and development of mission requirements.

VI.4.3.1 NTP Irradiation Facilities

a) Capsule Testing Facilities

Existing facilities will be used for fuel capsule testing. Irradiations at high flux levels will be required for meaningful tests for NTP application. A minimum of 1×10^{14} n/cm^{2}s is estimated to be required in order to achieve the required burnup in a relatively short period of time (provided it can be shown that flux levels do not affect fuel performance). Candidate facilities are the Advanced Test Reactor (ATR) and High Flux Isotope Reactor (HFIR) for steady state irradiations, and TREAT or ACRR for transient irradiations.

b. Single Element Testing

Single element testing was considered. It was found that power densities sufficiently high for some concepts could be provided, but not for all. Thus, the objectives of this fuel testing may have to be done by alternative means such as the Pipet facility for the particle bed reactor or its equivalent for other concepts. Expanding the capability of the Pipet facility to accommodate other concepts may be a practical solution. Should single element testing be undertaken, a new reactor or an existing reactor might be used. A new test reactor would take as long as the Pipet type facility and placing a hydrogen loop in an existing reactor, though feasible, may not be practical.

Potential general requirements for a single element test facility are presented in Table VI-9. These requirements are derived from the test requirement for fuel elements.

TABLE VI-9
POTENTIAL SINGLE ELEMENT FACILITY REQUIREMENTS

Fuel Element Form	Various Element Forms
Fuel Element Size	1.2 cm to 9 cm
Test Duration (per test)	10 min to 1 hour (multiple tests per element) (4.5 hrs total)
Hydrogen Flow (per element)	.01 to .1 lbm/s
Power Level (per element)	2 to 5 kW/cm^3
Fuel Test Temperatures	2500 K to 3600 K
Propellant Pressure	500 to 1000 psia
Test Frequency	4 elements per month (multiple tests per element)
Fuel Enrichment	70 to 93%
Instrumentation (for each element)	
Fuel Temperature Distribution	2500 K to 3600 K (multiple measurements)
Coolant Temperature (Inlet)	
Coolant Temperature (Outlet)	2500 K to 3600 K
Pressure	500 to 1000 psia
Flow Rate	.01 to .1 lbm/s
Neutron Power Detectors	2 to 5 kw/cm^3
Neutron Flux	$> 1 \times 10^{14}$ $n/cm^2/sec$
Fission Product Release	On line gamma detectors
Exit Gas Composition measurements CH_4, O_2, H_2, N_2	On line chemical measurements

A single element test facility should be able to accommodate intentional fuel failure for containment of fuel release in the coolant piping and release of fission products. Because high enriched uranium will be involved in fabrication of the fuel elements, appropriate safeguards per DOE orders need to be invoked to protect the high-enriched uranium. The reactor should be able to generate sufficient flux to achieve the specified power densities in the fuel elements for elements of varying design from prismatic carbide elements, particle bed elements, and cermets and should accommodate hydrogen pressures from 500 to 1000 psia.

c. Bundle Testing (Pipet or Nuclear Furnace Type) Facilities

A new facility will be required for NTP bundle testing which also may be used to test single elements. This facility would be used to determine element/element interactions and determine the consequences of fuel failure of one or more engine components such as those that may lead to loss of coolant or some other abnormal reactor condition, and if used to test single elements, to conduct element tests described in section VI.3.2.2. This facility, because of the statistics involved with testing a large number of elements, can yield the largest data base on fuel qualification from a performance and safety point of view.

At least 7 elements need to be tested in a cluster with each element being prototypical for the concept being tested in size, power density, and temperature. The preliminary requirements for bundle testing are similar to those for single element testing and are listed in Table VI-10. Further analysis will be required to determine the bundle size.

TABLE VI-10
PRELIMINARY BUNDLE FACILITY REQUIREMENTS DERIVED FROM FUELS TESTING REQUIREMENTS

Fuel Element Form	Various Fuel Elements
Fuel Element Size	1.2 cm to 9 cm
Test Duration (per test)	10 min to 1 hour (multiple tests per element) (4.5 hours total)
Hydrogen Flow (per element)	.01 to .1 lbm/s
Power Level (per element)	2 to 5 kW/cm^3 Fuel Test
Temperatures	2500 K to 3600 K
Propellant Pressure	500 to 1000 psia
Test Frequency	4 elements per month (multiple tests per element)
Fuel Enrichment	70 to 93%
Instrumentation (for each element)	
Fuel Temperature Distribution	2500 K to 3600 K (multiple measurements)
Coolant Temperature (Inlet)	
Coolant Temperature (Outlet)	2500 K to 3600 K
Pressure	500 to 1000 psia
Flow Rate	.01 to .1 lbm/s
Neutron Power Detectors	2 to 5 kw/cm^3
Neutron Flux	> 1 x 10^{14} n/cm^2/sec

Fission Product Release	On line gamma detectors
Exit Gas Composition measurements CH_4, O_2, H_2, N_2	On line chemical measurements

d. Engine Testing Facilities (TBD)

VI.4.3.2. NEP Irradiation Facilities

a. Capsule Testing

Facilities for capsule testing are expected to be existing facilities. The facilities for the NEP capsule irradiations need to have irradiation locations in high flux levels and for liquid-metal cooled fuels, high fast flux levels will be required. The test space required is the same as has been described above for the NTP capsule testing.

The EBR-II reactor is the most likely choice for irradiating fuel samples in capsule tests to be used for liquid metal systems. However, it can only accommodate small samples. FFTF could also be used, but it is expected to be shut down in mid FY-92 so it would not probably be available. Since samples would not necessarily have to be in contact with the appropriate coolants, the ATR or HFIR could also be used for testing capsule fuels provided that they have the appropriate fast spectrums. Further analysis would be needed to determine the spectrum and flux levels required.

A minimum flux of 1×10^{14} n/cm^2/s would be required in order to obtain required burnups in a relatively short period providing that there is not an effect of flux level on fuel performance. Further evaluation would be required to accelerate the irradiation time to achieve high burnups in as short irradiation time as possible. A lower flux level may be used with corresponding longer irradiation times. Two capsules are anticipated for the closed Brayton and the Rankine systems to handle the longer radiation times although the respective coolants are not being used in these capsules.

b. Single Element Testing

The top candidates for these types of facilities were EBR-II and FFTF. However, for EBR-II, the test space is limited to possibly small capsules since full-sized elements

are too large. FFTF, however, could accommodate the full sized elements, but it is scheduled to be shutdown at the end of FY-92 so it would not likely be available. Thus, there are no existing liquid metal cooled reactors that can be used for single element testing.

An alternative is to modify an existing water-cooled reactor with a liquid-metal-cooled, closed loop. Such a loop had been constructed in the Experimental Test Reactor (ETR) several years ago. However, this loop was sodium cooled rather than lithium cooled. The high fast flux in the ATR may also allow the use of a liquid metal loop in this reactor. Further analysis would be required to ascertain temperatures and power levels.

For single element testing, two test loops in existing reactors or two test reactor facilities would be required since both the liquid metal cooled reactor for use with a Li/K-Rankine cycle and a He/Xe cooled reactor for a Brayton cycle are being considered. These loops would be planned for an existing facility.

For the closed He/Xe cooled reactor systems, a new reactor or the same existing reactors considered for NTP fuels (see Facilities Panel Report[15]) could also be applicable. As an option to a new facility, a closed loop in the existing ATR or HFIR is appropriate. Inert gas rather than hydrogen would be required for the lower temperatures and power densities. As for the liquid-metal cooled loop, further analysis would also be required for a closed loop to determine operating temperatures and power levels.

If practical, another option may be to combine the closed He/Xe cooled element loop with the open hydrogen system described above for NTP. The closed loop would consist of pumps, heat exchangers, and instrumentation just as the open loop would have. Further study would be required to determine if this is indeed a viable option.

c. <u>Reactor Testing</u>

The basic support facilities for testing NEP reactors will be required, but the reactor itself is expected to be fabricated as part of the concept development. The feasibility issues are expected to be resolved during the single element testing with the appropriate information generated for fuel performance, reliability, safety, and code validation and verification.

VI.4.3.3 FUEL DISPOSAL FACILITIES

Facilities for reprocessing and disposing of the irradiated fuels generated during fuels development and testing and during ground testing will require the development of new processes and facilities for doing the reprocessing.

VI.5 PROGRAM PLAN

In preparing a program plan, numerous plausible scenarios could be considered. A broad comprehensive program could be defined that led to an orderly downselection of the best candidate fuels for nuclear furnace and engine testing. The cost of such a program could be estimated using generally accepted cost estimating procedures. However, it is clear that there would be many perturbations to such a scheme. As has already become apparent, funding in the early years will be considerably smaller than required for the abovementioned comprehensive program and there could be significant interest in near-term flight tests which would require acceleration of the early "front runner" fuel types. Without clearer definition of these plausible scenarios it is not possible to perform a detailed evaluation. Furthermore, an exercise in developing detailed cost/schedule plans is beyond the scope of the ad-hoc volunteer panel. We have chosen a compromise approach for illustrative purposes. The case represents a generally broad-based early R&D program with somewhat greater emphasis on one of the concepts.

In essence, our example is a hybrid approach in which the NERVA tested fuel is used as the first generation fuel for the early missions. In parallel (at least to the extent possible), higher performance fuels would be developed to meet the somewhat longer term objectives (as defined in Section II) of SEI. It needs to be stated that there was only minimal discussion on this strategy at the Panel meetings (since the early flight test scenarios became defined after the panel work was almost completed). In addition, there was far from unanimity in the choice of the NERVA composite fuel on the early focus fuel given the known problems and issues. However, a draft DOE fuels plan used this example for their plan and it serves as a reasonable basis for that purpose. If a different fuel (e.g., the cermet fuel) is used, the test program would have to be modified accordingly. A national program would include an initial period of preselection prior to embarking on a full fledged

development program. If an accelerated mission were to be undertaken, the preselection process would include careful consideration of all fuel types and a decision on the early development fuel would be made based on current state of development to present day requirements, etc. The selection for the fuel for longer term use would involve a detailed evaluation as outlined in the plan below.

The estimate was performed for the following scenario. The fuels development and tested were assumed to follow two paths. The first was to qualify a first generation fuel with lowest development risk, and accept a lower performance than SEI needs. The second was to develop the required higher performance fuel in a comprehensive, technically justifiable fashion. Six fuel forms would be initially selected for development. These six fuel types are : (1) carbide fuels for prismatic elements, (2) particle bed carbide fuel elements, (3) UO_2 cermet elements, (4) UN cermet elements, (5) UN pin-type elements, and (6) UO_2 (thermionic) pin-type elements. The priority for the fuels development is listed below for the six fuel forms based upon nuclear thermal and nuclear electric propulsion systems.

<u>Nuclear Thermal Propulsion</u>	<u>Nuclear Electric Propulsion</u>
Prismatic Carbide Fuels	UN Pin Fuels
Particle Bed Fuels	UN Cermet Fuels
UO_2 Cermet Fuels	Particle Bed Fuels
	Thermionic Fuel Elements

Since the prismatic carbide elements and the particle bed elements for NTP offer the greatest growth potential they are ranked high. The particle bed element offers a potential for high performance, but has a low demonstrated technology level, and it has some significant feasibility issues that place it as a medium risk. For the prismatic carbide elements, the composite carbide elements had been tested in a reactor and demonstrated at low temperatures for a short time. These elements pose a lower risk of development, but may have limited development potential for temperatures above 2450 K. They may have to operate at even lower temperatures

to establish acceptable safety margins with the corresponding loss of specific impulse. The primary impetus for their development is potential use in lower performance early missions. Therefore, high-temperature carbide fuels need to be developed. The UO_2 cermets are ranked third because of the high potential to retain fission products, as well as potential safety and performance advantages, but they may result in the heaviest engine. The solid solution prismatic fuel elements depend on developing stable, high-melting fuels that do not crack, and therefore impose a high-risk, long-term development effort.

For NEP systems, the UN pin fuels are ranked highest because of the potential to utilize SP-100 experience and flight qualify small (100 and 500 kW(e)) systems relatively early to demonstrate the feasibility of these Rankine systems. Advanced UN pin fuels would be evaluated for liquid metal coolant temperatures greater than 1500 K. The UN cermets offer the potential for longer life-times and higher burnups than UN fuel pins. The feasibility of the UN cermet needs to be determined from the research and development efforts, and this system needs substantial investment. Closed-Brayton systems are ranked below the liquid metal-cooled systems because of the projected higher masses of these systems with large radiators and/or high radiator temperatures. Particle bed reactor based closed Brayton systems will be considered, however, because of the potential for high burnups and/or fission product retention. The thermionic systems have the potential for robotic or cargo missions at the 1 to 5 MWe level. In view of the current activity in the ongoing DOE and Air Force programs, and because of questions about extrapolations to higher power, this system is ranked below the others for near-term funding.

A fuels and materials working group consisting of members from different DOE laboratories, NASA field sites, participating universities, and the private sector should be formed to review and assess the fuel development and testing activities and submit recommendations, as an advisory group, to the project office. At each test facility for the irradiated tests involving single element or bundle tests, a Data Integrity Group (DIG) should be formed to evaluate and assess the test data for its integrity and uncertainty in the test measurements. This function would be to qualify the data for code validation, reliability and safety assessments.

Significant activities for the comprehensive program for the development and testing of carbide, nitride, and oxide fuels are summarized in Tables VI-11, VI-12, and VI-13 respectively. Major milestones are denoted by an "*" by the activities. These milestones are based on a slow funding ramp rate for FY-93 and FY-94. The early emphasis for this program is the general research and development efforts for the carbide, oxide, and nitride fuels. The prismatic carbide fuels are initiated early with emphasis on the composite fuel. Single elements could be ready for irradiation testing by August 1994 and this testing completed by July 1996. With the completion of the small sample irradiation by September 1995, an advanced composite fuel could be ready for testing by September 1995. The particle bed fuel development for space exploration purposes is initiated late in FY-92 so that a single particle bed element is not ready for irradiation testing until August 1996. This does not consider the work scheduled by the Air Force SNTP program. Progress in that program might be able to accelerate this considerably. The other carbide fuel forms are deferred to a later date as well as the specific fuel forms for the nitride and oxide fuels. Although the UO_2 cermet fuel is delayed, these elements can begin testing by January 1995 since UO_2 properties and behavior have been well established under LWR programs.

If the funding level were reduced to a level that choices had to be made on fuel development without the benefit of screening tests on the basic fuels suggested earlier, the decisions would need to be based on the concept designs and a determination of the performance potential of the various concepts. The most likely scenarios would put the nitride and oxide pin element work at low priority (because of ongoing work on these) and put carbide based fuel (composite prismatic, solid solution prismatic and PBR) high on the list because of high temperature potential. This is not a clear cut choice, however, because of all of the other features that need to be considered and will require careful consideration.

VI.6 SUMMARY

A detailed fuels development plan needs to be integrated with the overall systems design and development activity. For this initial stage of the space

TABLE VI-11
RECOMMENDED CARBIDE FUELS MILESTONES

Research & Development		
Develop UC & MC Fabrication Process	7/91	
Melting points	8/92	
Carbide Stability	2/93	
Laboratory Scale Demonstration	10/93	*
Fuel Fabrication for Irradiated Tests	7/93	
Evaluate NTP Irradiation Performance	9/95	*
NEP Capsule Irradiation	9/96	
Evaluate NEP R&D	12/96	*
NTP Fuel Element Irradiation		
NTP PBR Fuel Element Fabrication Process	2/96	
Initiate Single Element Irradiation Testing	8/96 (10/97)	*
NTP PBR Fuel Element Irradiation	7/98 (9/99)	
NTP Evaluate PBR Fuel Element Fuel	12/98 (11/99)	*
NTP Composite Fuel Element Fabrication Process	2/94	
Initiate Single Element Irradiation Testing	8/94 (10/97)	*
NTP Composite Fuel Element Irradiation	7/96 (9/99)	
NTP Evaluate Composite Fuel Element Fuel	12/97 (11/99)	*
NTP Solid Solution Fuel Element Fabrication Process	10/97	
Initiate Single Element Irradiation Testing	4/98	*
NTP Solid Solution Fuel Element Irradiation	3/00	
NTP Evaluate Solid Solution Fuel Element Fuel	8/00	*
NEP Fuel Element Irradiation		
NEP PRR Fuel Element Fabrication	2/96	
Initiate Single Element Irradiation Testing	9/98	*
NEP PBR Fuel Element Irradiation	5/01	
NEP Evaluate PBR Fuel Element Fuel	8/01	*
NEP Composite Fuel Element Fabrication	2/94	
Initiate Single Element Irradiation Testing	8/94	*
NEP Composite Fuel Element Irradiation	9/99	
NEP Evaluate Composite Fuel Element Fuel	11/99	*
NEP Solid Solution Fuel Element Fabrication	10/97	
Initiate Single Element Irradiation Testing	4/98	*
NEP Solid Solution Fuel Element Irradiation	5/01	
NEP Evaluate Solid Solution Fuel Element Fuel	8/01	*

TABLE VI-11
RECOMMENDED CARBIDE FUELS MILESTONES (cont.)

<u>Hardware Fabrication</u>	
NTP Hydrogen Loop Fabrication	10/97
NTP Hydrogen Loop Fabrication	10/97
NTP Capsule Fabrication	6/93
NEP Capsule Fabrication	6/93
Single Element Test Reactor Support Facilities	9/98

( ) Late schedule driven by facility availability or process availability
a. Test schedules require earlier dates for facilities to be operating
b. Support facilities do not include operating reactor
c. For an advanced NERVA fuel, Initiate irradiation testing 9/95, complete NTP irradiation testing 8/97, evaluate fuel element performance 4/98

TABLE VI-12
RECOMMENDED NITRIDE FUELS MILESTONES

<u>Research & Development</u>		
Develop Stable UN Fuel	2/93	
Determine UN Stability and Compatibility	4/94	*
NEP Capsule Irradiation	11/96	
Evaluate UN Swelling & Fission Product	5/97	*
<u>NEP Fuel Element Irradiation</u>		
Fabricate UN Cermet Fuel	2/00	
Initiate UN Cermet Irradiation Testing	11/98	*
NEP UN Cermet Fuel Irradiation	6/02	
Evaluate UN Cermet Fuel	8/02	*
Fabricate UN Pin Fuel	7/98	
Initiate UN Pin Irradiation	6/96 (7/98)	*
NEP Pin Fuel Irradiation	1/00 (2/02)	
Evaluate UN Pin Fuel	4/00 (6/02)	*
<u>Hardware Fabrication</u>		
NEP Liquid Metal Loop Fabrication	10/97	
NEP Capsule Fabrication	6/93	

TABLE VI-13
RECOMMENDED OXIDE FUELS MILESTONES

<u>Research & Development</u>		
UO2 Stability & Compatibility	3/92	
Kinetics of UO2/Cladding Interaction	12/92	
Capsule Irradiation	9/96	
Evaluate UO2/Refractory Alloy Performance	1/97	*
<u>NTP & NEP Fuel Element Irradiation</u>		
Fabricate UO_2 TFE's for Testing	7/96	
Initiate TFE Irradiation	6/95 (10/97)	
NEP TFE Loop Irradiation	1/99 (3/00)	
Evaluate TFE Performance	4/99 (7/00)	*
Fabricate UO_2 Cermets	1/95	
Initiate UO_2 Cermet Irradiation	5/94 (10/97)	*
NTP UO_2 Cermet Irradiation	4/96 (8/98)	
Evaluate UO2 Cermet Performance	7/96 (12/98)	*

( ) Late schedule driven by facility availability or process availability

exploration program, a generic plan has been developed that is based upon fuels requirements derived from preliminary mission requirements. These requirements necessitate fuels for nuclear thermal propulsion to operate at temperatures greater than 3000 K to achieve 925 second specific impulse and operate at power levels at more than 5 MW/ℓ with thrust to weight ratios less than 10. For these high temperatures and multiple restarts, fission product release should be minimized. For nuclear electric propulsion, the power densities in the fuels are less than 0.5 kW/cm^3 with operating temperatures as high as possible commensurate with reliability and life-times to achieve specific masses less than 10 kW(e)/kg.

The fuel development plan is also based upon the available design information on the proposed NTP concepts. In order to maximize options, it was decided to exploit commonality between the various fuel types to the maximum. If sufficient resources were to be available, six fuel forms should be developed; prismatic solid carbide fuels, particle bed fuels, two cermets of UN and UO_2 dispersed in tungsten or tungsten based alloys, and UN and UO_2 pin fuels. The selection of these fuels for development represent the fuels development for 19 different solid core propulsion systems. The feasibility issues for these six fuel forms are discussed and center on the maximum temperature/time capability of these fuels.

The fabrication issues for these six fuels are described, which involve for the first part recapturing the fabrication technology for the 1960s with improvements for the advanced fuels that need to be developed. The testing strategy for the fuels will depend upon the available funding (and cash flow) for the project. For this work a general plan has been prepared for one plausible scenario. Testing of these fuels starts with non-nuclear testing involving measurements of the physical, mechanical, and thermal properties of the carbide fuels and to a certain extent the nitride fuels. Other non-nuclear testing involves the transient thermal testing of fuel samples and elements, and hot hydrogen flow testing on a laboratory scale. The nuclear testing consists of capsule testing in an existing facility to get fuel irradiation data for fission product release, fuel performance, and screening data as early as possible. The

capsule tests are followed by fuel element tests with more refined fuel designs for resolving the feasibility issues for these fuels.

A fuels properties and performance data base would be assembled to document the data for design information, reliability and safety assessments.

Facilities are discussed that will be required for fuel fabrication, testing, and fuel disposal. Initially, for capsule and fuel element testing, the fuels would be fabricated on a laboratory scale, and for the driver cores, if required, and the reactor and engine testing, the fuel will be fabricated on a pilot plant level. All of the capsule testing can be performed in one facility, since the use of different coolants are not required. Different facilities for fast or thermal spectrums will probably be required. The plan would then be to reprocess the fuel to remove the actinides and fission products. The actinides could then be burned in the Integral Fast Reactor (IFR) if that option is proved feasible, the fission products stored in a waste repository for less than 300 years, and the HEU (high enriched uranium) returned into the fuel cycle.

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VII. MATERIALS TECHNOLOGY DEVELOPMENT PLAN

INTRODUCTION

In preparing the materials development plan, a set of programmatic assumptions were made in addition to the ones listed in Section II. It is assumed that the program intends to proceed through an orderly concept evaluation process leading to the down-selection of the nuclear propulsion system appropriate to meet the requirements of the manned Mars mission currently included in the Space Exploration Initiative (SEI). In order to plan for the timely results from the materials technology, it was assumed the nuclear propulsion program would evolve through four phases, as shown in Fig. 7-1. In Phase 1, competing NEP and NTP concepts will be evaluated leading to the selection, possibly, of an optimum NEP and NTP concept around 1995. In Phase II, these two concepts would be evaluated in greater detail leading to the down-selection of a single concept around the year 2000. Ground testing of the selected reactor/propulsion system should be completed by approximately 2005, Phase III. Phase IV would be a flight qualification phase with the objective of taking the ground tested concept and qualifying it for flight by 2015 or 2016.

The recommended materials technology program has been structured to support this program during each of the four phases. During Phase I this program must develop an initial engineering data base for candidate materials adequate to support the conceptual design activities to be performed during this phase of the program and complete by 1995 a cursory assessment of major materials feasibility problems to be utilized in the NEP and NTP concepts downselection process. In Phase II the initial materials engineering data base must be expanded to support the enhanced design activities; additional feasibility issues associated with the NEP and NTP systems must be assessed to support the down-selection decision to be made in 2000. The emphasis of Phase III is different than the previous phases. By this time the materials of construction for the reference system should be determined. A major objective of this phase is the development of the comprehensive engineering data base necessary to obtain approval to operate the ground test reactor/propulsion system in 2004. The

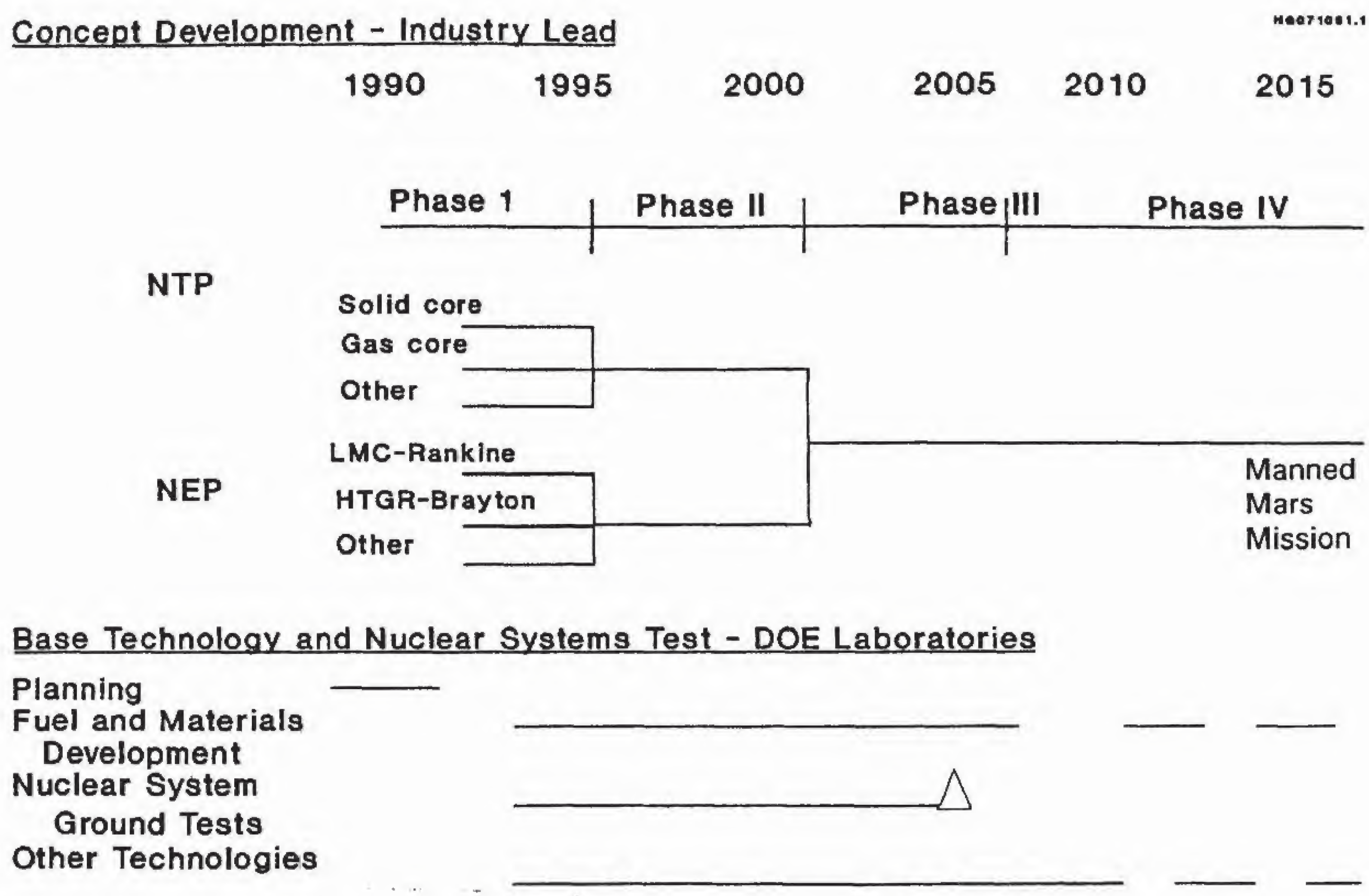


Fig. 7.1 One of Several Conceptual Plans for the Evolution of the Space Nuclear Propulsion Program for Manned Mars Mission

panel has insufficient information at this time to determine the nature of the materials activities associated with Phase IV, the flight qualification phase.

VII.1 CANDIDATE MATERIALS AND OPERATING CONDITIONS

As indicated above, both NEP and NTP systems will be initially evaluated for the nuclear propulsion application. These systems are made up of a number of complex subsystems. Each subsystem, in turn, has unique operating conditions and materials challenges. The purpose of this section is to provide a brief description of these operating conditions, identify the diverse materials that are being considered for nuclear propulsion applications, and summarize the major technical issues associated with these materials.

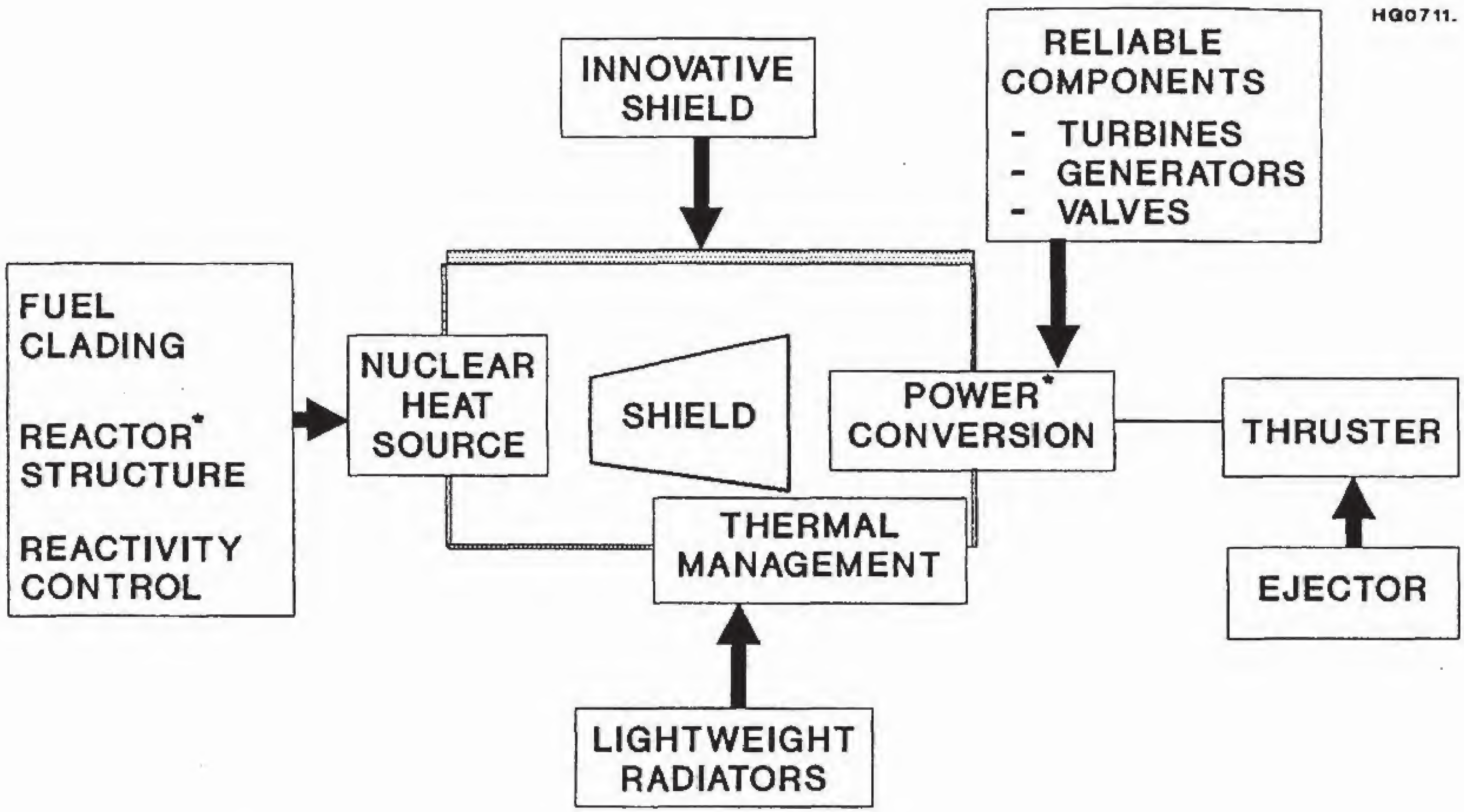
Nuclear Electric Propulsion

Operational requirements for the proposed NEP concepts call for structural and control materials to withstand continuous long-term operation for 20,000 h or longer at operating temperatures ranging from 1000 K for radiators to 2000 K for in-core components. In this range of operating temperatures, materials used for fuel cladding, reactor structural, and reactor control applications must demonstrate (1) effective load-carrying capability; (2) tolerance to neutron irradiation at a fluence as high as 5.0×10^{22} n/cm^2; (3) compatibility with candidate reactor fuels; (4) compatibility with candidate coolants and working fluids, which include alkali metals and inert gases; and (5) fabricability into needed product forms and required component configurations.

For any of these NEP systems, five major subsystems can be identified – nuclear heat source, radiation shield, power conversion, thermal management, and electric thruster, as shown in Fig. 7-2. The operating conditions for these subsystems are widely different and are summarized in Table VII-1. Although no detailed designs exist for these conceptual systems, candidate materials of construction for the major components associated with these subsystems were identified by the materials subpanel, see Table VII-2.

Nuclear Thermal Propulsion

Operational requirements for the proposed NTP concepts call for structural and control materials to withstand periodic operation for a cumulative time of 6000 h at



*For in-core thermionics concepts, power conversion material challenges are associated with the reactor components physically located in the reactor.

Fig. 7.2 Diverse Materials Challenges Exist in Each of the Five Nuclear Electric Subsystems

Table VII.1 Anticipated Operating Conditions for Major NEP Subsystems

Subsystem	Nominal temperature (K)	Environment	Radiation fluence (n/cm^2)	Lifetime goal (h)
Nuclear heat source	1350 to 1900 (to 2000)*	Liquid metal or inert gas	10^{22}	6×10^4
Shield	500 to 1000	Major components (i.e., hydride and structural materials)	10^{15} to 10^{20}	6×10^4
Power conversion	1350 to 1900	Liquid metal or inert gas	10^{12}	6×10^4
Thermal management	900 to 1200	Liquid metal	10^9	6×10^4
Electric thruster	TBD	Hydrogen helium or lithium	TBD	1×10^4

*In-core thermionic emitter temperature may approach 2000K.

Table VII.2

Summary of currently identified candidate materials organized by major NEP subsystem

Subsystem	Major component	Alloys and metal-matrix composites	Ceramic and ceramic composites	Carbon/carbon composite and graphitics	Coatings
Nuclear heat source	Fuel cladding, reactor structure, and re-entry structure	**REFRACTORY ALLOYS** Tungsten-based W-25Re W-HfN CVD-W Soviet single crystal Molybdenum-based Mo-7Re Mo-41Re Mo-HfN Soviet single crystal Tantalum-based T-111 ASTAR 811C ASTAR 1211C ASTAR 1511C Niobium-based Nb-1Zr Nb-1Zr-0.1C Nb-1Zr-1W-0.1C **METAL MATRIX COMPOSITE** W-HfC/Nb-1Zr		Carbon/carbon composites	
	Reactivity control	Beryllium	B_4C BeO Boral (Al/B_4C)		Tribological
Power conversion	Turbine, shell, and valves	See refractory alloys above	BeO	C/C turbine	

Table VII.2 (cont.)

Radiation shield	Neutron shield		LiH ZrH		
	Gamma shield		W-Ni-Fe		
	Structural	Stainless steels Be			Hi-emissivity
Thermal management	Pumps	Refractory alloys above			
	Piping and ducts	Refractory alloys from above		Metal-lined C/C composites	
	Radiators	Refractory alloys Titanium-based alloys Beryllium		Metal-lined C/C composites	Hi-emissivity
Thruster	Ejector	Porous tungsten			

temperatures to 3000 K for the fuel support system. At this temperature, materials used for fuel support, in-core structure, and fuel coating must demonstrate compatibility with fuel, resistance to fuel interactions resulting from operation, compatibility with the hydrogen propulsion media, and capability to keep the fuel contained during operation.

NTP systems which serve as the basis of this plan are based on hydrogen-cooled solid-core nuclear heat sources. For any of these solid-core NTP systems, five major subsystems can be identified – propellant tank, propellant pump, radiation shield, nuclear heat source, and thruster nozzle (see Fig. 7-3). The operating conditions for each of these subsystems are widely different and are summarized in Table VII-3. Again no detailed designs exist for these conceptual systems; however, candidate materials of construction for the major components associated with these subsystems were identified by the materials subpanel (see Table VII-4).

VII.2 SUMMARY OF MATERIALS APPLICATIONS

In Tables VII-2 and VII-4, approximately 100 different materials are identified as potential candidates for use in the systems. To further assess the materials technology issues associated with NTP and NEP applications, a table was prepared summarizing all materials technical issues that will need to be evaluated during the first three phases of the program (Table VII-5). In many cases specialized or limited facilities will be required to investigate these issues and quantify the magnitudes of affected parameters. A summary identifying the special or limited facilities that may be needed and provided highly preliminary requirements for these facilities has been prepared and is presented in Table VII-6.

In many cases the operating environments and anticipated design requirements do not exceed the known performance limits of these materials. In other cases the suggested materials are expected to perform satisfactorily, but confirmation of this performance is required. In a limited number of situations, it is not known if the minimum acceptable system performance can be achieved with the currently known materials. A major objective of this plan is to identify these situations and to particularly note where these unknowns could impact the qualification of long lead technology activities such as fuel and power conversion systems.

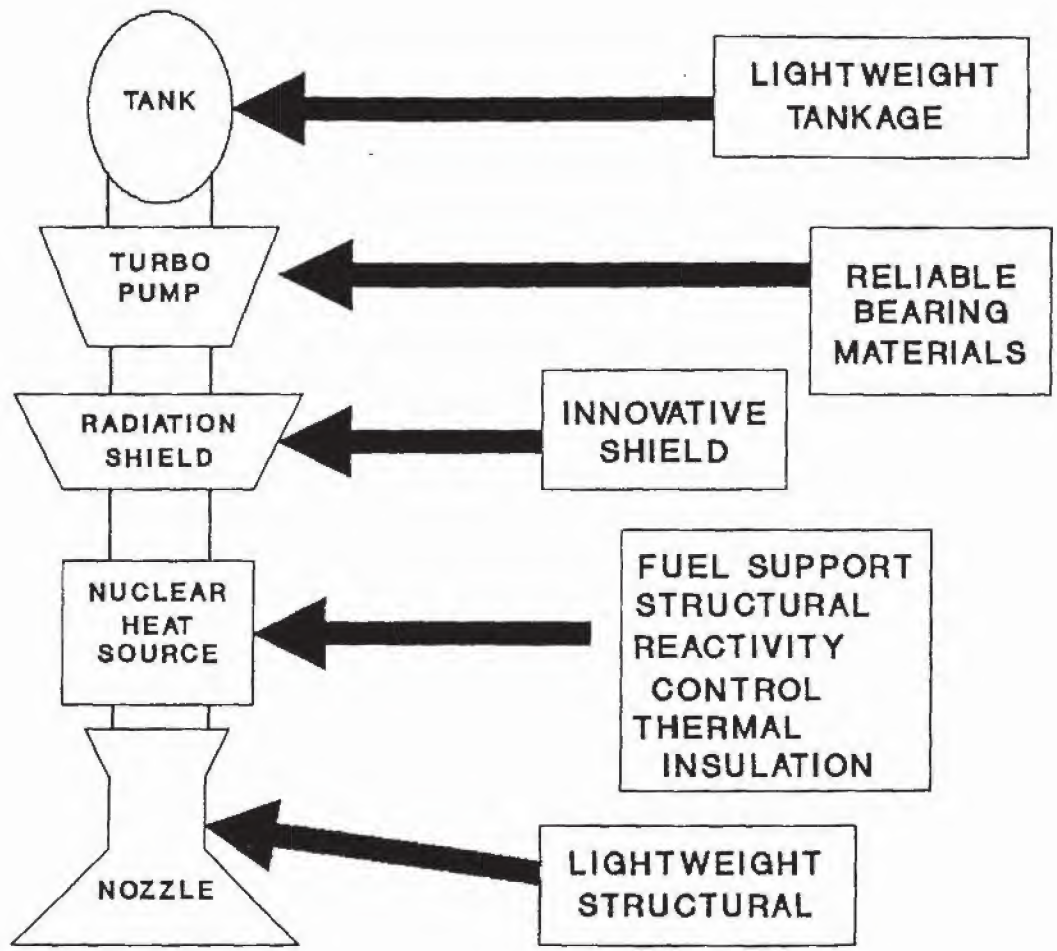


Fig. 7.3 Diverse Materials Challenges Exist in Each of the Five Nuclear Thermal Sybsystems

TABLE VII.3
ANTICIPATED OPERATING CONDITIONS FOR MAJOR NTP SUBSYSTEMS

Subsystems	Nominal Temperature (K)	Environnment	Neutron Fluence (n/cm^2)	Mission Lifetime Goal (h)
Propellant tank	4 to TBD	Cryogenic hydrogen	TBD*	10^4
Turbo pump Pump Turbine	 4 to TBD 900 to 1300	 Cryogenic hydrogen Hot hydrogen	TBD	10^4
Radiation shield	900	Components	TBD	10^4
Nuclear heat source	20 to 3000	Cold hydrogen to hot hydrogen	TBD	10^4
Nozzle	3000	Hot hydrogen	TBD	10^4

* Estimates for neutron fluences for these subsystems are not currently available.

Table VII.4

Summary of Currently Identified Candidate Materials Organized by Major NTP Subsystems

Subsystem	Major component	Candidate materials			
		Alloy metal matrix composites	Ceramic and ceramic composites	Graphites, carbon/polymer matrix, and carbon/carbon composites	Coatings
Propellant tank	Tank	Aluminum alloy Al-Li alloys		Carbon/polymeric matrix composites	
Turbo pump	Pump Low-pressure High-pressure	Iron-based alloys A 286 Type 310 stainless steel Aluminum-based alloys 1100 2075 2119-T6 3003 4043 5052 6061 7175 Titanium-based alloys Ti-5Al-2.5Sn Ti-5Al-2.5Sn EL1 Ti-6Al-4V Ti-6Al-4V EL1			

Table VII.4 (cont.)

Summary of Currently Identified Candidate Materials Organized by Major NTP Subsystems

Subsystem	Major component	Candidate materials			
		Alloy metal matrix composites	Ceramic and ceramic composites	Graphites, carbon/polymer matrix, and carbon/carbon composites	Coatings
Exhaust nozzle		Iron-based alloys A286 Nickel-based alloys Inconel 718 Inconel 625 Mo and Mo-based alloys		Carbon/carbon composites	Hydrogen barrier

Table VII.4 (cont.)

Summary of Currently Identified Candidate Materials Organized by Major NTP Subsystems

Subsystem	Major component	Candidate materials			
		Alloy metal matrix composites	Ceramic and ceramic composites	Graphites, carbon/polymer matrix, and carbon/carbon composites	Coatings
	Turbine	Nickel-based alloys Ni-200 Inconel 625 Nichrome Hastelloy B Waspaloy MAR-M-246 RENE-41 Hastelloy X Inconel X-750 Inconel 600 Inconel 718 Inconel 61 RA330		Hydrogen protected C/C composite	Hydrogen barrier (see fuel and core support above)
Radiation shield		W-Ni-Fe (gamma shielding) Al alloys for structure	BATH lead/boron carbide, Al, TiH LiH Borated ZrH		

Table VII.4 (cont.)

Summary of Currently Identified Candidate Materials Organized by Major NTP Subsystems

Subsystem	Major component	Candidate materials: Alloy metal matrix composites	Ceramic and ceramic composites	Graphites, carbon/polymer matrix, and carbon/carbon composites	Coatings
Nuclear heat source	Fuel and core	Springs Inconel 718 W-25Re Other supports Mo	TaC Thermal insulation ZrO ZrC	Pyrolytic graphite POCO graphite ZTA graphite Graphfoil	Hydrogen barrier ZrC NbC TaC HfC Two-phase CVD coatings
	Reactivity control	Beryllium B-Cu	B_4C ZrH (moderator)		Tribological
	Pressure vessel	Al-based alloy 7075-T73 7079-T6 22190T87 Ti-based alloy Ni-based alloys Inconel 718 Inconel 625 Iron-based alloy A286		Hydrogen protected C/C composited	Hydrogen barrier (see fuel and core support above)

Table VII.5 Critical Issues and Facility Needs of Space Nuclear Propulsion Material Activities

	Types of candidate materials				
Major material attributes	Alloys	Composites	Ceramics	Coatings	Magnetic and Superconducting
1. Mechanical and physical properties Critical issues	· Characterize creep properties at proposed operating temperature · Characterize tensile properties · Determine ductile to brittle transition of Mo- and W-based alloys · Characterize low-cycle fatigue and creep-fatigue interactions for NTP materials · Validate performance under complex loading	<u>Metal-Fiber Metal-Matrix</u> · Determine ROM property estimates of candidates - tensile - creep - ductile to brittle transition - fatigue - toughness · Characterize stability to thermal cycles · Assess effect of matrix/filament interactions (aging effects) on mechanical properties <u>Ceramic Matrix</u> · Determine the ROM properties of candidate in proposed environments · Determine feasibility of a design methodology applicable to brittle materials <u>Carbon Matrix</u> · Determine ROM properties in proposed operating environments	<u>Structural</u> · Demonstrate adequacy of properties of candidate ceramics from prototype component shapes - fracture - tensile - fatigue <u>Control Applications</u> · Determine ROM property estimates - compressive creep - flexure - thermal conductivity <u>Radiation Shield</u> · Characterize properties - tensile - thermal expansion - thermal conductivity	<u>Environmental, Protection Wear, and Emissivity</u> · Confirm that coatings do not degrade mechanical properties - thermal cycle - thermal stability <u>Emissivity</u> · Characterize hemispherical emittance	TBD

Table VII.5 Critical Issues and Facility Needs of Space Nuclear Propulsion Material Activities (cont.)

	Types of candidate materials				
Major material attributes	Alloys	Composites	Ceramics	Coatings	Magnetic and Superconducting
1. Mechanical and physical properties (cont.) Facility needs	· Approximately ten ultrahigh-vacuum, high-temperature creep machines · One high-vacuum, high-temperature vacuum tensile machine · Five pressurized tube creep test facilities capable of testing in alkali-metal, vacuum, and hydrogen	· Approximately ten ultrahigh-vacuum, high-temperature creep machines · One high-vacuum, high-temperature vacuum tensile machine · Five pressurized tube creep test facilities capable of testing in alkali-metal, vacuum, and hydrogen	· Approximately 20 high-temperature, environmental control mechanical property test units · Specialized mechanical properties test facilities for handling hydride materials · Specialized thermal properties test facilities for measuring hydride materials	· Approximately ten ultrahigh-vacuum, high-temperature creep machines · One high-vacuum, high-temperature vacuum tensile machine · Five pressurized tube creep test facilities capable of testing in alkali-metal, vacuum, and hydrogen	TBD

Table VII.5 Critical Issues and Facility Needs of Space Nuclear Propulsion Material Activities (cont.)

	Types of candidate materials				
Major material attributes	Alloys	Composites	Ceramics	Coatings	Magnetic and Superconducting
2. Compatibility Critical issues	NEP-GCR-Brayton Cycle · Assess potential of mass transfers in circulating gas coolant - small-scale test - larger circulating loops NEP-LMC-Brayton Cycle · Assess degradation at inert-gas/alkali-metal interface (IHX) NEP-LMC-Rankine Cycle · Determine compatibility of candidate alloys with coolant - static - dynamic NTP · Assess degradation of candidate NTP materials to hydrogen Fuel/Coolant · X-reactor tests of fuel/coolant interaction with candidate fuel cladding - static - dynamic	Metal Matrix · Assess filament/matrix compatibility · Assess compatibility with candidate coolants - H_2 - alkali-metals - inert-gases Ceramic Matrix · Assess compatibility with candidate coolants - H_2 - alkali-metals - inert-gases Carbon Matrix · Demonstrate that protective coatings will allow use of C/C composites with - H_2 - alkali-metals - inert-gases · Demonstrate feasibility of refractory metal liners for C/C heat pipe applications	Structural and Control Applications · Assess compatibility with candidate coolants and working fluids - H_2 - alkali-metals - inert-gases Radiation Shield · Assess compatibility with neutron and gamma shield materials thermal management system and structural containment materials.	Environmental Protection · Assess compatibility with appropriate materials and environments - substrates - H_2 - alkali-metal - inert-gas - low-pressure oxygen - atomic oxygen Wear · Demonstrate adequacy of candidate coatings - tribological - substrate compatibility Emissivity · Assess compatibility with - substrates - low-pressure oxygen - atomic oxygen	TBD

Table VII.5 Critical Issues and Facility Needs of Space Nuclear Propulsion Material Activities (cont.)

	Types of candidate materials				
Major material attributes	Alloys	Composites	Ceramics	Coatings	Magnetic and Superconducting
2. Compatibility (cont.) Facility needs	· Alkali-metal compatibility testing laboratory - static - flowing · High-temperature inert-gas compatibility laboratory - static - flowing · High-temperature, high-pressure hydrogen compatibility laboratory - static - flowing	· Alkali-metal compatibility testing laboratory - static - flowing · High-temperature inert-gas compatibility laboratory - static - flowing · High-temperature, high-pressure hydrogen compatibility laboratory - static - flowing	· Alkali-metal compatibility testing laboratory - static - flowing · High-temperature inert-gas compatibility laboratory - static - flowing · High-temperature, high-pressure hydrogen compatibility laboratory - static - flowing	· Alkali-metal compatibility testing laboratory - static - flowing · High-temperature inert-gas compatibility laboratory - static - flowing · High-temperature, high-pressure hydrogen compatibility laboratory - static - flowing · High-temperature tribological test laboratory · Atomic oxygen plasma test laboratory	TBD
3. Irradiation tolerance Critical issues	· Characterize candidate alloys for - swelling - mechanical properties degradation - phase stability	<u>Metal Matrix, Ceramic Matrix, and Carbon Matrix</u> · Characterize candidate systems for - swelling - mechanical properties degradation - phase stability	<u>Structural, Control, and Radiation Shield</u> · Characterize candidate systems for - swelling - mechanical properties degradation - phase stability	· Characterize candidate systems for - swelling - mechanical properties degradation - phase stability	TBD
Facility needs	· Appropriate reactor · Material test fabrication and assembly area · PIE capability	· Appropriate reactor · Material test fabrication and assembly area · PIE capability	· Appropriate reactor · Material test fabrication and assembly area · PIE capability	· Appropriate reactor · Material test fabrication and assembly area · PIE capability	

Table VII.5 Critical Issues and Facility Needs of Space Nuclear Propulsion Material Activities (cont.)

	Types of candidate materials				
Major material attributes	Alloys	Composites	Ceramics	Coatings	Magnetic and Superconducting
4. Processing and component fabrication Critical issues	· Demonstrate feasibility of producing candidate innovative materials · Demonstrate feasibility of producing candidate materials into needed product forms (i.e., tube, sheet, and plate) · Demonstrate weldability of candidate materials · Establish facility for producing high-quality material to support subsystem and system testing	Metal Matrix · Demonstrate feasibility to fabricate candidate filaments · Demonstrate feasibility of fabricating a matrix composite in product form · Demonstrate ability to join composites Ceramic Matrix · Demonstrate feasibility to fabricate components of prototypic size · Demonstrate potential to fabricate components with acceptably small flow sizes - Demonstrate feasibility of cost-effective NDE method Carbon Matrix · Demonstrate feasibility of fabricating large structural component · Demonstrate feasibility of joining C/C components · Identify, qualify coatings to protect C/C in proposed operating environment · Demonstrate NDE method to assure structural adequacy and coating integrity	Structural Control Applications · Demonstrate the feasibility of fabricating prototypic size components defect "free" · Demonstrate feasibility of adequate NDE methods · Demonstrate feasibility of joining prototype-size components Radiation Shield · Demonstrate feasibilty of fabricating large complex shapes required for neutron shield	· Demonstrate feasibility of producing uniform quality coatings · Resolve problem with joining components and maintaining coating quality · Demonstrate feasibility of cost-effective NDE method	TBD

Table VII.5 Critical Issues and Facility Needs of Space Nuclear Propulsion Material Activities (cont.)

	Types of candidate materials				
Major material attributes	Alloys	Composites	Ceramics	Coatings	Magnetic and Superconducting
4. Processing and component fabrication (cont.) Facility needs	· Integrated refractory alloy fabrication facility · Component welding and joining facility	Metal Matrix · Filament fabrication facility · Laboratory-scale composite fabrication area · Prototype composite fabrication area Ceramic Matrix · Filament fabrication facility · Laboratory-scale composite fabrication area · Prototype composite fabrication area Carbon Matrix · Filament fabrication facility · Laboratory-scale composite fabrication area · Prototype composite fabrication area	Structural and Control Applications · Integrated laboratory-scale ceramic fabrication facility · Industrial-scale integrated ceramic fabrication facility Radiation Shield · Integrated hydride material fabrication facility	· Laboratory-scale coating facilities - plasma spray - chemical vapor deposition - PF plasma	TBD

Table VII.6

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
1. Mechanical properties			
Ultrahigh-vacuum, high-temperature creep machine	• Characterize the creep properties of candidate materials • Provide the data necessary to down-select candidate materials • Provide preliminary engineering data required for conceptual design • Yield data sufficient to down- or out-select concepts	• Needed during the first year of program • Test facility should have capability to - 1700 K - 10^{-10} torr vacuum - facilitate automated data acquisition • Proven and reliable test methods used and QA practices followed	• Limited facilities in the country - most committed to long-term SP-100 test - remaining have been inactive for many years • Test devices available commercially at about $250K each
High-temperature tensile machine	• Characterize the tensile and fatigue properties of candidate materials in alkali metal, inert gas, and hydrogen • Provide data necessary for down-selection of materials • Provide preliminary engineering data required for conceptual design • Yield data sufficient to down- or out-select concepts	• Needed during the first year of program • Vacuum test facility should have capability to - 1700 K - capability of a wide range of strain rates - perform both low- and high-cycle fatigue - vacuum to 10^{-7} torr • Hydrogen test facility should have capability to - 2500 K - capability of a wide range of strain rates - perform both low- and high-cycle fatigue - hydrogen pressures to 10 K	• Limited known qualified facilities • Are committed to SP-100 • Twenty to thirty facilities available - Appear to be committed to NASP program

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
1. Mechanical properties (cont.) Pressurized tube creep test	• Inexpensive method to obtain long-term creep performance data on candidate alloys • Provide data for preliminary system design • Yield data needed to optimize system life versus performance trades	• Needed by the second to third year of the program • Vacuum furnace capable of - 1350 to 1700 K - 10^{-10} torr - running uninterrupted for thousands of hours • Hydrogen test furnace capable of - 1900 to 2500 K - hydrogen pressures to 1000 psi - running uninterrupted for hundreds of hours • Proven and reliable test methods used and Quality Assurance practices followed	• Number and availability of such facilities is not known • Availability is unknown
High-temperature mechanical properties test facilities for ceramic and ceramic components	• Characterize the tensile and fatigue properties of candidate materials • Provide data necessary for down-selection • Yield preliminary engineering data required for concept design • Yield data sufficient to down or-out-select concepts	• Needed during first year of program • Vacuum test facility with capability to - 1700 K - perform both low- and high-cycle fatigue - vacuum to 10^{-5} torr - minimize specimen bending to less than 0.1%	• Numerous machines available in ceramic community - more machine capability anticipated

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities			
Description	Mission/objective	Requirements	Status
2. Compatibility Alkali metal compatibility laboratory	• Characterize the alkali metal compatibility of candidate materials - assess dissimilar metal combinations - mass transfer phenomena - qualify fabrication and joining methods • Provide data necessary for conceptual through final design • Yield data for concept down-selection or optimization	• Static test facilities needed first year, thermal convection loops needed by third year, and pumped loops by fifth year • Extensive experience with design and operation of alkali-metal/refractory-alloy tests • Intimate knowledge of the procedures to safely handle alkali metals • Refractory and superalloy welding, fabrication, and annealing facilities • Vacuum vessels for static tests capable of - temperatures to 1700 K - vacuum to 10^{-8} torr • Thermal convection and/or pumped loop tests capable of - 1 to 10K h continuous operation - maximum temperatures to 1700 K - vacuum vessels of sizes to 12 ft diam by 20 ft long with low leak rate and vacuum to 10^{-8} torr	• Limited sites with small-scale test facilities • Limited sites with needed large-scale vacuum test capability; significant modifications anticipated

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities			
Description	Mission/objective	Requirements	Status
2. Compatibility (cont.) Inert gas compatibility test laboratory	• Characterize the compatibility of candidate materials at high temperature in-inert gas environment - assess dissimilar metals - mass transfer phenomena - evaporation phenomena • Provide data necessary for conceptual through final design • Yield data for concept down-selection and optimization	• Needed in first year of program • Extensive experience with design and operation of high-temperature inert-gas tests with refractory alloys and superalloys • Demonstrate experience in procedures in handling inert gases and test facilities safely • Refractory and superalloy fabrication, welding, and annealing facilities • Test apparatus capable of - temperatures to 1900 K - vacuum to 10^{-5} torr	• Facilities should exist with modifications in support of the HTGR Program
Hydrogen compatibility test laboratory	• Characterize compatibility of candidate materials at high temperatures in inert-gas environment - assess dissimilar metals - mass transfer phenomena - evaporation phenomena - ductility loss - low-temperature embrittlement - fatigue and creep property degradation • Provide data necessary for conceptual through final design • Yield data for concept down-selection and optimization	• Needed in the first year of program • Extensive experience with design and operation of high-temperature hydrogen test with a variety of materials • Demonstrated experience in the safe operation of high-temperature, high-hydrogen tests • Refractory and superalloy plus structural ceramic fabrication facilities • Test apparatus capable of - temperatures to 2500 K - hydrogen pressure to 1000 psi	• Availability unknown • Very specialized facilities • Should exist in support of - coal gasification and liquefaction programs - NASP - chemical propulsion

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities			
Description	**Mission/objective**	**Requirements**	**Status**
2. Compatibility (cont.) High-temperature tribological test laboratory	• Characterize the wear and galling characteristics of moving and bearing surfaces operating at high temperatures • Provide data necessary to shown that feasibility issues associated with gall and wear problems have been mitigated • Generate failure mode data and reliability statistics	• Needed by fourth or fifth year of program • Extensive experience with design and operation of high-temperature tribological facilities • Refractory alloys, superalloy, ceramic, and coating processing experience and capability • Test apparatus capability - temperatures to 2500 K - test environment may include o vacuum to 10^{-8}torr o alkali metals o hydrogen to 1000 psi - rotational and/or reciprocating motion - appropriate diagnostic methods	• Limited capability in place for SP-100 Project - temperature limited to 1350 K - vacuum environment only
Atomic oxygen	• Characterize and assess the degradation of candidate structural materials (particularly refractory alloys) to atomic oxygen - ductility loss - alkali attack • Provide data necessary for conceptual design • Yield data for materials and concept down or out selection	• Need cursory test ability in 2-year program • Test apparatus capable of simulating atomic oxygen environment	• Numerous facilities are thought to be available (i.e., LANL, NASA-LeRC)

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
3. Irradiation tolerance			
Material test reactor	• Provide a facility capable of exposing materials in materials test assemblies to prototypic irradiation environments for subsequent characterization of irradiation damage effects	• Must identify test reactor in the first year to allow completion of test and PIE to support down-selections in year four or five of program • One or more separate reactors may be required to simulate NEP and separately NTP in-core and outside of core environments; specific requirements include - fast spectrum (NEP) - thermal spectrum (NTP) - capable of maintaining material environments of alkali metals or inert gas - capable of maintaining a predetermined test material temperature that may range from 800 to 1900 K - support the capability for an instrumented test	• Several candidate DOE reactors are available - FFTF - EBR II - ATR - HFIR - others
Material test fabrication and assembly	• This facility is an integral part of the materials irradiation test activity • This facility, including its staff, will design materials test, build and instrument the test vehicle, install test specimens, ship test vehicle to reactor, and oversee the installation into the test reactor	• Must identify material test and assembly in the first year to allow completion of test and PIE to support down-selection in year four or five of program • Experience with design of experiments for reactor selected • Experience in meeting quality assurance requirements for test design and assembly • Suitable fabrication, assembly, and inspection capability	• Capabilities exist at several DOE laboratories

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
3. Irradiation tolerance (cont.) PIE/hot cells	• This facility (or facilities) is an integral part of the materials irradiation test activity • One facility will disassemble the test vehicle after reactor exposure • One or more facilities will perform material characterizations and report on results	• Must identify PIE/hot cells in the first year to allow effective test design and implementation • Facility must have the following - experience with testing the candidate materials - equipment necessary to perform needed tests o neutron radiograph o profilometry o metallography and ceramography o microanalysis and microanalytical equipment o mechanical properties tests - tensile impact, and bend • Appropriate quality assurance and environmental, health, and safety experience	• Capability exists at several DOE laboratories

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities			
Description	Mission/objective	Requirements	Status
4. Processing Refractory alloy	• Recapture alloy fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needed for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities - melting - ingot breakdown - secondary and final product fabrication capability for sheet, plate, and tubing - annealing - inspection • Facility must have refractory alloy fabrication experience • High level of quality assurance practice is essential <u>Laboratory Scale</u> • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible <u>Commercial Scale</u> • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed around the year 2000	• Limited qualified facilities available at DOE labs, government labs, or industry • Expect there to be limited qualified commercial manufacturers willing to commit the resources to produce hardware for the ground test portion of the program

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
4. Processing (cont.) Ceramic matrix composites	• Develop fabrication practices needed for new materials • In the near term, fabricate the product needed for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities - preform preparation - matrix fabrication - sintering - machining - inspection • Facility must have previous ceramic matrix component fabrication experience • High level of quality assurance practice is essential <u>Laboratory Scale</u> • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible <u>Commercial Scale</u> • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed around the year 2000	• Limited qualified facilities available at DOE labs, government labs, or industry • Limited qualified commercial manufacturers

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
4. Processing (cont.)			
Metal matrix	• Develop fabrication practices where needed for new materials • In the near term, fabricate the product needs for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities - melting and/or matrix deposition processes - secondary and final product fabrication capability for sheet, plate, and tubing - annealing - joining and machining - inspection • High level of quality assurance practice is essential	
		Laboratory Scale • The capability to produce small quantities of prototypic components in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		Commercial Scale • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed around the year 2000	• Probably no commercial manufacturers capable of making hardware needed for space nuclear propulsion activities

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
4. Processing (cont.)			
Carbon composite	• Recapture past fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needed for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities - preform lay-up and weaving - impregnation - secondary and final product fabrication capability for sheet, plate, and tubing - carbonization - joining and machining - inspection • Facility must have carbon/carbon fabrication experience • High level of quality assurance practice is essential	
		Laboratory Scale • The capability to produce small quantities of prototypic materials in needed product forms will pace initial material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		Commercial Scale • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed around the year 2000	• Limited qualified commercial manufacturers

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities

Description	Mission/objective	Requirements	Status
4. Processing (cont.)			
Monolithic ceramic	• Recapture previous fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needs for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities - blending, pressing, and sintering - machining - fabrication capability for sheet, plate, and tubing - inspection • High level of quality assurance practice is essential	
		Laboratory Scale • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Several qualified facilities available at DOE labs, government labs, or industry
		Commercial Scale • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed around the year 2000	• Probably no commercial manufacturers prepared to support projection; probably willing to scale up

Table VII.6 (cont.)

Facility Needs for Space Nuclear Propulsion Materials Activities			
Description	**Mission/objective**	**Requirements**	**Status**
4. Processing (cont.)			
Radiation shield (hydride)	• Recapture previous fabrication practices where needed or develop practices for new materials • In the near term, fabricate the product needs for initial screening and feasibility tests • In the longer term, fabricate products needed by major subsystems and system demonstration tests	• Facilities will need the following fabrication capabilities - blending, pressing, sintering or melting - machining - encapsulation - inspection • Facility must be designed for safe operation when handling hydride materials or other toxic materials • High level of quality assurance practice is essential	
		<u>Laboratory Scale</u> • The capability to produce small quantities of prototypic alloys in needed product forms will pace initial fuel and material performance tests that must be initiated as soon as possible	• Limited qualified facilities available at DOE labs, government labs, or industry
		<u>Large Scale</u> • The capability to produce large quantities of hardware will be needed to support subsystems and system tests to be performed around the year 2000	• Expect there to be limited qualified commercial manufacturers willing to commit the resources to produce hardware for the ground test portion of the program

VII.3 RELEVANT MATERIALS TECHNOLOGIES FROM OTHER PROGRAMS

Although a large number of diverse materials are required to support the SNP concepts, a wealth of materials technology is available from previous and current space nuclear power programs, civilian reactor programs, and ongoing aerospace programs. The purpose of this section is to provide a summary of this information.

VII.3.1 System for Nuclear Auxiliary Power

Extensive refractory alloy development occurred in the 1960s and early 1970s as part of the System for Nuclear Auxiliary Power (SNAP) program. Several niobium- and tantalum-based alloys were shown to be compatible with UO_2 and UN fuel in irradiation tests to 10,000-h at 1265 K and in out-of-reactor fuel/cladding/coolant compatibility tests in flowing lithium at temperatures to 1300 K. The tantalum-based alloys were shown to be compatible with flowing alkali metals in tests to 10,000 h at 1470 K and 3000 h at 1640 K. These SNAP programs were terminated in the early 1970s, and no prototypical alkali-metal-cooled reactors having ceramic fuel clad with refractory alloys were built or operated.

The refractory alloys developed for the SNAP programs are potential candidates for selected NEP applications. However, these alloys cannot be considered state-of-the-art materials; and development efforts will be required to qualify them for SNP applications.

VII.3.2 ROVER/NERVA Program

A nuclear propulsion division was established at the Los Alamos National Laboratory in April 1955 under the joint sponsorship of the Air Force and the Atomic Energy Commission. Most of the ROVER/NERVA work was sponsored by the joint office of the Atomic Energy Commission (now Department of Energy) and the National Aeronautics and Space Administration called the Space Nuclear Propulsion Office. The Los Alamos program was entitled ROVER, and the Aerojet General and Westinghouse program was entitled NERVA.

VII.3.2.1 Uranium Fuel

The fuel development activities from these programs have been discussed in Section VI. Of interest from the materials point of view are improvements of the beads and precursors used for the graphite matrix.[1] While the ANL cermet program [2]

focussed primarily on fuels development, as did the NASA-LeRC program,[3] data on high temperature behavior of refractory alloys were developed that will be of use in the present nuclear propulstion program.

VII.3.2.2 Zirconium Hydride Moderator

Using the work performed for the SNAP program and the Aircraft Nuclear Propulsion (ANP) programs as a base of information, fabrication parameters were developed to provide ZrH moderator materials with controlled properties and hydrogen contents. The purpose of the moderator was to reduce the inventory of uranium in the reactor core. The Pewee reactor was designed as a test bed for the evaluation of full-size fuel elements and other core components. This reactor core required one-fourth to one-tenth the number of fuel elements of other reactor core tests (402 fuel elements).

VII.3.2.3 Support System

Carbide-composite development was pursued to improve the core support. Coated graphite support blocks and cups had been used but hydrogen corrosion and erosion during testing stimulated a search for a less-reactive material. Investigations found that a hot-pressed composite, 46 v/o carbide (TaC-NbC)-54 v/o graphite, CVD coated with TaC or NbC performed very well. Compression tests showed less than 1% deformation at 3000 psi load for 30 min at 3300 K. Support blocks and fuel element tips were machined from the pressings for the core.

VII.3.2.4 Coating Development

It was realized early that hydrogen and graphite would react to form methane, acetylene, and other hydrocarbons at the anticipated high temperatures of a rocket engine. Further, the graphite loss from hydrogen corrosion during reactor operation would seriously affect the reactor neutronics. A fuel element coating effort was undertaken in 1959 to develop thin (0.25- to 0.50-mm-thick) NbC or ZrC coatings to act as a barrier to hydrogen attack. Significantly greater effort was expended on ZrC coatings.

VII.3.2.5 Component Development

A vigorous program for the development of non-nuclear engine components accompanied the reactor and engine test programs. The principal components were the

main coolant pumps, the valves and actuators, the nozzle assembly, the reactor pressure vessel, radiation shielding, and the controls and instrumentation.

VII.3.3 SP-100 Project

The SP-100 Project was initiated in 1983 and work is currently in progress in the reactor ground test phase. The SP-100 space power system utilizes a liquid-metal-cooled fast reactor. Thermal energy from the nuclear heat source is converted to electrical energy using thermoelectric modules. Since 1983, the project has developed a comprehensive design for a generic flight system and is now developing the detailed design for a prototype reactor to be ground tested starting in 1998. A prototypical section of the thermal management and power conversion system is also scheduled for fabrication and for ground testing starting in 2001. Because of the progress made to date, this project is a major source of materials technology relevant to NEP concepts and also provides some important materials options for NTP systems. Materials technologies from the SP-100 Project highlighted in this plan include (1) refractory alloys for high-temperature structural applications, (2) reactor control materials, and (3) radiation shield materials.

VII.3.3.1 Refractory Alloys

In the early phase of this Project, niobium-, tantalum-, and tungsten-based alloys were evaluated; and niobium-based alloys were selected for structural applications. Although the niobium-based alloys cannot operate at temperatures as high as other candidates, this family of alloys was considered the most developmentally mature, thereby offering the lowest technical risk to the project. Specifically, the Nb-1Zr alloy was considered the best candidate on the basis of its extensive mechanical properties data base; successful experience in the design, fabrication, and operation of high-temperature liquid-metal systems; and favorable fuel compatibility experience. Building from this experience, the Project has selected an Nb-1Zr-0.01C alloy as the reference structural material because of its attractive high-temperature creep properties.

The SP-100 Project is generating a data base for niobium-based alloys, which will be extensively expanded over the course of the next 5 years. Specifically, the SP-100 Project has characterized the compatibility of Nb-based alloys with UN fuel at

temperatures to 1400 K, generated a comprehensive data base of mechanical properties and irradiation effects for temperatures to 1400 K, and developed the procedures for fabrication of the complex components needed for the operation of high-temperature alkali-metal systems.

Although the refractory alloys of principal interest to the SP-100 Project are those based on niobium, important progress has been, or will be, made with other refractory metals and alloys, specifically the tantalum-based alloy ASTAR 811C and rhenium. With regard to rhenium, the project has optimized and demonstrated the ability to draw rhenium into a thin-wall small-diameter tube which is bonded subsequently to the interior of a niobium alloy tube. This bimetallic tubular structure serves as the cladding for the uranium-nitride fuel used in the SP-100 reactor.

VII.3.3.2 NEP Radiation Shield

The reference radiation shield system for the SP-100 Project utilizes LiH for neutron attenuation and a W-Ni-Fe alloy for primary and secondary gamma attenuation. The optimum composition of the LiH has been established, and methods for fabrication of the LiH into the unique shapes required for this application have been determined. The LiH is contained within a stainless steel shell to maintain a hydrogen overpressure and thus prevent large-scale dissociation. To support this design, the project is generating a comprehensive data base on the compatibility of LiH with other shield components and on the mechanical and thermal properties of LiH throughout the temperature range of operation. In addition, data on the effects of neutron and gamma radiation on swelling and on the above properties are planned to be obtained in the near future.

VII.3.4 Multiwegawatt Space Power Program

The Multimegawatt (MMW) Space Power Program was initiated in 1985 to develop space nuclear power systems capable of generating tens to hundreds of megawatts of electric power in space. An important part of this program was the MMW materials technology task. This task continued through 1989 providing materials technology information of significant value to the SNP program. These activities included work on refractory alloys, ceramics, and ceramic-matrix composites.

VII.3.4.1 Refractory Alloys

In the area of refractory alloys, the MMW materials task carried out work on Mo-HfN and ASTAR 811C alloys, refurbished specialized high-temperature mechanical properties testing facilities, and assessed and evaluated the previously published technical data of candidate MMW materials.

VII.3.4.1.1 Mo-HfN Alloy

Work was performed to characterize and optimize a Mo-1.86 Hf alloy for MMW applications. To achieve high-temperature strength properties, the alloy was to be internally nitrided after the desired structural component had been fabricated. Preliminary work performed showed that the alloy in the nitrided condition had high creep strength and should be compatible with both lithium and hydrogen. Limited quantities of the alloy were successfully rolled into sheet and drawn into small-diameter thin-wall tube. In addition, small coupons were successfully welded.

VII.3.4.1.2 ASTAR 811C

ASTAR 811C is a tantalum-based alloy containing tungsten, rhenium, hafnium, and carbon. On the basis of testing performed in the early 1970s as part of the SNAP program, this alloy was shown to have excellent compatibility with alkali metals and high-temperature creep properties that make it 10 to 15 times stronger than the Nb-1Zr alloys at 1300 to 1400 K. In reviewing the SNAP program activities associated with this alloy, no indication was found that thin-wall small-diameter tubing had been fabricated from this alloy by traditional industrial methods. As a part of the MMW materials task, three ingots of ASTAR 811C were made. One of the ingots was hot extruded to a tube shell and approximately 100 ft of 0.300-in. diam by 0.025-in. wall tubing was successfully fabricated by conventional tube drawing methods.

VII.3.4.1.3 High-Temperature Mechanical Properties Test Facilities

Due to the limited availability of high-temperature creep and tensile testing facilities, the MMW program initiated efforts to refurbish two high-temperature, ultra-high-vacuum, uniaxial creep test stands located at Lawrence Livermore National Laboratory. Significant capital investment was made to refurbish this equipment and enhance the data acquisition equipment. Although the facilities were never qualified for testing, they represent an important and valuable resource to the SNP program.

VII.3.4.1.4 High-Temperature Materials Information

The MMW materials task attempted to perform a thorough review of the previously published technical information available on candidate MMW materials. These efforts, coupled with similar efforts in support of the SP-100 Project, identified approximately 755 relevant documents on candidate high-temperature materials. An annotated bibliography summarizing these documents was issued in 1990.[4]

This previously published data was also analyzed to generate preliminary estimates of the mechanical and thermal physical properties for selected candidate materials. The data were summarized in a MMW materials properties handbook. The information in this handbook provided a source of reference materials properties data for the MMW program and represents an excellent source of materials properties data needed for the current planning phase of the nuclear propulsion program.

VII.3.4.2 Ceramic Matrix Composites

Two activities were performed in the area of ceramic matrix composites. In the first activity, a composite consisting of continuous graphite fiber in a TiB_2 matrix was fabricated for possible thermionic emitter applications. In the second task, a thermodynamic assessment of the stability of candidate monolithic and ceramic-matrix-composite materials were evaluated in high-temperature alkali metals simulating Rankine-cycle systems, inert gases simulating Brayton-cycle systems, and hydrogen for open-cycle applications. This assessment showed that candidate ceramic materials have limited applications in alkali-metal and hydrogen systems.

VII.3.5 Hydrogen/Oxygen Rocket Engine

The experience gained in the materials selection and development of hydrogen/oxygen rocket engines has direct applicability to nuclear rocket engines. In particular the hydrogen feed system turbomachninery for chemical rockets can be used directly in nuclear thermal propulsion systems. The effects of high pressure hydrogen on the embrittlement of rocket engine materials has been extensively studied and design methods have been developed to mitigate the effects.

VII.3.5.1 RL10 Engine

Production chemical rocket engine experience began early in 1957. The RL10 was the first hydrogen/oxygen rocket engine designed and built for a flight application. The RL10 is an expander cycle engine. The current production model, the RL10-A-4, is capable of 22,800 lb of thrust at an ISP of 449 at a mixture ratio of 5.5. The engine has proven to be reliable for over 30 years partly because the expander cycle requires relatively low turbine temperatures and propellant pressures.

The materials used in the RL10 are predominantly stainless steels and aluminum alloys. Both alloy systems are preferred because of their demonstrated resistance to hydrogen embrittlement, flexibility in fabrication, and cryogenic ductility. The turbines operate at temperatures below 390 K and are constructed of aluminum. Aluminum provides low start inertia for the rotor and low manufacturing cost. The housings are aluminum castings, which provide thermal expansion match with the impeller and reduce weight. The main chamber and nozzle are fabricated from 360 brazed 300-series stainless steel tubes. Few of the materials have been changed since 1957 because the system has been low cost and reliable, while still being adaptable to meet new performance goals.

VII.3.5.2 J2 and J2-S Engines

The J-2 engine provided highly reliable performance for the second stage and third stage of the Saturn vehicle. The propellants were liquid oxygen and liquid hydrogen with an I_{sp} of 425 seconds and a mixture ratio of 5.5:1. The chamber pressure was 760 psi with a thrust level of 230,000 pounds. Several nickel base alloys were utilized in the construction of the J-2. K Monel was utilized for the oxygen turbopump impeller and the turbine shaft was Inconel X-750. Other components of the oxygen turbopump were fabricated from aluminum alloys and stainless steel. In the fuel turbopump the impeller and inducer were Monel K 500. The turbine disk and injector were made from Inconel 718 forgings and the manifold from Hasteloy C. Turbine blades were cast from Inconel 713C. No failures were observed in the J-2 attributable to Hydrogen-Environment Embrittlement (HEE). From the subsequent knowledge of HEE developed at Rocketdyne, as well as from other investigators, the operating conditions in the J-2 were not severe enough to cause a failure, i.e. low chamber pressure and short exposure times.

The J-2S liquid oxygen/liquid hydrogen rocket engine is a simplified, higher thrust and performance version of the J-2. The chamber pressure was 1,200 psi with a thrust level of 265,000 pounds. The engine has separate oxidizer and fuel turbopumps driven in series by hot gases tapped off the main combustor. The oxidizer turbopump was the same as the J-2 but a different fuel turbopump was used. Titanium-5 Al-2.5 Sn-ELI was used extensively in the inducer section while Inconel 718 forgings were used for the housing and the turbine disk. The throttlable J-2S engine has multiple restart capability, a propellant utilization system, variable mixture ratio, and a low thrust operating capability.

VII.3.5.3 Space Shuttle Main Engine (SSME)

The Space Shuttle Main Engine (SSME) is a liquid hydrogen-oxygen staged combustion engine with a chamber pressure of 3280 psi with a thrust level of 512,000 pounds. The severe operating conditions of hydrogen environment, rapid start and stop temperature transients and high temperatures and pressures offer an unique set of material challenges not found in any other current materials applications.

The heart of the SSME is the powerhead. The powerhead is comprised of the hot gas manifold, main injector, main combustion chamber, fuel and oxygen preburner and the fuel and oxygen high pressure turbopumps.

The high pressure fuel turbopump (HPFTP) provides a high pressure, high-volume flow of liquid hydrogen fuel to the preburner injectors, the main combustion chamber the nozzle and other cooling circuits of the engine. All of this fuel eventually reaches the main injector where the combustion process is completed. The HPFTP is a three-stage centrifugal pump that uses two interstage diffusers to pass the hydrogen from one stage to the next.

The pump is driven by a two stage, hot gas turbine at rotational speeds up to 37,000 rpm and develops a maximum of 55.9×10^6 W of power at a discharge pressure of 6900 psi and a head of 180,000 ft. The three impellers are made from a titanium alloy, but the pump and turbine housing, the discharge volute and the main pump shaft are Inconel 718. As in the oxidizer pump, the housing is a welded assembly of forgings, castings and preformed sheet metal. In the fuel pump the thermal differentials which must be accommodated by the Inconel 718 housing are particularly severe. At the

turbine to pump interface, less than 60 mm separates liquid hydrogen at minus 400 F from preburner hot gas combustion products (hydrogen-rich steam) at 1450 F.

One of the early concerns about the use of Ni-base alloys in the SSME was the potential for HEE. In the low temperature solution treated condition (1,750 F), Inconel 718 is particularly embrittled; the ratio of notched tensile strength in high-pressure hydrogen to high-pressure helium is 0.59. Walter et al[5] attributed this to the presence of the orthorhombic Ni_3Nb (delta) phase present in the microstructure. Solution treating at 1900F eliminated this phase and the notch strength ratio rose to 0.76. The smooth specimen reduction of area ratio also increased from 0.3 to 0.5 respectively, with an acceptable level of room temperature ductility. These improvements in ductility and toughness made Inconel 718 acceptable for use in the SSME. However, since Inconel 718 remains somewhat susceptible to HEE, several design philosophies were adopted for use of Inconel 718 in hydrogen fuels. One technique utilized was to minimize the strains to 2.0 % in components which were exposed to hydrogen near room temperature. This was accomplished by designing pressurized components to have surface strains less than the strain-to-crack initiation strain (approximately 2.0%) in hydrogen or by proof loading pressurized components prior to exposure. Where strains were higher, copper plating was used on components exposed to high pressure hydrogen at temperatures less than 310 F. A minimum thickness of 0.1 mm of copper was required to prevent embrittlement. The use of Incoloy 903 as a liner and as a weld overlay was also employed to serve as a barrier to prevent hydrogen embrittlement.

Mar-M-246 is a Ni-base superalloy used for turbine blades. It is also subject to HEE at the turbopump operating conditions. Several cases of cracking attributable to HEE have been observed and one failure has been attributed to this form of cracking. The use of shot peening on portions of the blades to place the surfaces in compression has eliminated most of the turbine blade surface crack problem.

In the early period of use, it was thought that Inconel 718 and other nickel-base alloys were immune to internal hydrogen embrittlement (IHE). As more and more time is accumulated on SSME engines it has been shown that this is not the case. To verify this a series of tests were conducted on fully hardened Inconel 718 (1900 F solution treat) after thermal charging with hydrogen at 1200 F for 15 minutes[6]. When

uncharged control specimens were tested in hydrogen at room temperature, a 57 percent drop in reduction in area (RA) was recorded. Thermally charged specimens, when tested in hydrogen at room temperature, exhibited an additional 50 percent drop in RA. Gold plating can be used to reduce hydrogen effects. When gold plated specimens are tested in hydrogen, a 30 percent loss of RA is observed. Gold plating prior to thermal charging reduced the degree of degradation but did not entirely prevent all degradation resulting from thermal charging: no loss of strength is observed, but an approximate 50 percent loss of RA is observed. Therefore, while plating is effective in minimizing HEE, it may not be an effective means of controlling IHE.

From this knowledge of HEE and IHE, design practices, process changes and protection schemes have led to the successful use of Ni-base and other embrittled alloy systems in the hydrogen fueled SSME.

The turbopumps designed for the Alternate Turbopump Development (ATD) Program were required to be line-replaceable units for the current space shuttle main engine (SSME). These pumps have utilized materials technologies which have been tested for resistance to hydrogen embrittlement and high strength and ductility at their respective operating environment.

The housings for both the hydrogen and oxygen pumps are Inconel 718 castings, produced in a fine-grained condition for high strength and ductility at cryogenic temperatures and improved weldability. Use of Inconel 718 is limited to temperatures below 150 K because of hydrogen embrittlement. Plating is not used to protect materials from the effects of hydrogen. In the turbine housings where hydrogen is present at pressures up to 4000 psi and 815 K, the iron-based superalloy A-286 is used. The forgings are thermomechanically processed to increase the mechanical properties to a level near Inconel 718.

Static structures in the turbine which operate below 920 K are fabricated of Inconel 909, a nickel-based alloy which has a low coefficient of expansion and shows limited effect on mechanical properties due to the hydrogen environment. The low coefficient of expansion provides additional control of clearances in the turbine to improve efficiency.

VII.3.6 National Aerospace Plane

The National Aerospace Plane (NASP) Materials and Structures Augmentation Program was started in March 1988 with the purpose of developing advanced materials which could significantly impact the structural efficiency of the X-30 experimental flight vehicles. For this program, the maturity of each particular family of material was to be demonstrated by the fabrication and testing of typical airframe and engine structure components. The specific families of materials being developed are: monolithic titanium aluminides (TiAl) for non-actively cooled structural applications; titanium matrix composites (TMC) for non-actively cooled structural applications; refractory composites, including both carbon/carbon materials and ceramic composites; high-conductivity composites, including monolithic copper alloys, graphite-copper composites, and beryllium alloys; and high specific creep strength materials (HSCSM), including gamma (TiAl) monolithic alloys and composites, and tau ($TiAl_3$) monolithic alloys and composites for heat exchanger applications.

VII.3.6.1 Carbon/Carbon Composites

While the initial program plan for carbon/carbon materials included application as primary structure, the major effort has been directed to thermal protection systems for both the high heat flux airframe areas and for the engine cowl for reentry conditions. Matrices with and without additions to inhibit oxidation have been evaluated. Because the propulsion system and the interplanetary vehicle will not cycle into and out of an air environment, the inhibited matrix appears to be an attractive choice for the cowl using a silicon nitride coating which provides a 1915 K temperature capability and could be used for primary structure.

Carbon matrix composites reinforced with silicon carbide or carbon fibers are being tested for the highest temperature areas of gas turbine engines, principally exhaust nozzle liners. These materials must be protected from oxidation for applications within earth's atmosphere and attack by the hydrogen propellant; but they are stable at temperatures exceeding 2200 K in inert environment. They also provide high specific strengths and stiffness with useful damage tolerance. Their use for SNP applications will require development of a hydrogen-resistant coating.

VII.3.6.2 Refractory Alloys

Recent work on the NASP Program has concentrated on demonstrating the feasibility of refractory alloys for use as high-temperature plumbing lines and very-high-temperature heat exchangers in the combustor section. A nominally 50-50 Mo-Re alloy was chosen primarily for its thermal margin for the combustor heat flux application and its acceptable ductility at all temperatures, including cryogenic hydrogen.

VII.3.6.3 Other Materials

The NASP Program is investing considerable effort in both gamma (TiAl) and alpha-two (Ti_3Al) titanium aluminides, titanium alloys, titanium matrix/SiC fiber components, copper alloys, copper/graphite matrix composites, and Be-Al. At this time, these materials have proven to be either incompatible with high-temperature hydrogen or do not have the high-temperature performance required to meet the performance objectives of the SNP.

VII.3.7 Relevant Advances In Other Aerospace Programs

In addition to the programs cited above, additional aerospace programs in the past decade have led to significant advances in materials technology for aerospace applications. One such example is the emergence of Al-2% Li alloys as a spacecraft structural material. With low density and high stiffness imparted by the lithium addition, Al-Li alloys are now the material of choice for satellite structures and structural spacecraft hardware. A large cylindrical component has been successfully fabricated from Al-Li and is used as the payload adaptor for the Titan IV program. Al-Li is considered a candidate material for cryogenic propellant tankage in the next-generation NASA launch vehicle. Current research to optimize the mechanical properties of alloys containing 4% or 5% Li is underway, and it may be expected that these materials will be available during the lifetime of the SEI program.

SDI-related programs are also yielding information with great potential value to the development of NTP or NEP technologies. One such example is the experience gained in the manufacture of Re tubing and its fabrication into a 2000°C spacecraft attitude control system. Unlike the Re tubing used as a lining in the SP-100 Project, the Re tubing developed for SDI is a stand-alone high-pressure structural tube which must face rigorous high-temperature and high-pressure operating conditions. Other SDI-related

technologies such as sensors and "compactness" will be relevant to SEI related programs as well.

VII.3.8 The SNTP Program

The ongoing Air Force Space Nuclear Thermal Propulsion (SNTP) program, which was recently declassified, is producing data on various high temperature materials. At the time this report was being prepared, not enough information from the program was available to include in this compilation. However, the data from the SNTP program needs to be included in the materials data base as the overall nuclear propulsion program progresses.

VII.4 COMPREHENSIVE TECHNOLOGY PLANS

General materials requirements necessary to meet the system goals of the nuclear propulsion concepts and a summary of the candidate materials for these systems have been identified in this plan. From the assumed objectives of each phase of the nuclear propulsion development program, specific time-sequenced actions for each of the candidate materials were developed. The purpose of this section is to summarize these proposed actions for each family of candidate materials through Phase I of the nuclear propulsion program.

These specific materials actions have been organized under the following topics:

- management;
- alloys—including refractory, nickel-, aluminum-, titanium-, and iron-based alloys;
- composites—including metal-, ceramic-, polymeric-, and carbon-matrix composite materials;
- ceramics—including ceramics for reactivity control, structural applications, thermal insulation, and radiation shielding; and
- coatings—including those for applications such as hydrogen protection and reduction wear and galling between high-temperature moving parts.

VII.4.1 Management

Centralized management of the materials technology activity is needed to ensure that materials technology issues are adequately and cost-effectively resolved on a

schedule supporting SNP program milestones. Given the large number of candidate materials that are being considered and the variety of technical issues to be resolved, management of these activities will be challenging.

VII.4.1.1 Specific Management Actions

This plan recommends three specific management actions to ensure effective management: (1) forming a Materials Advisory Committee (MAC), (2) holding periodic materials technology symposia, and (3) preparing and maintaining an SNP materials properties handbook.

VII.4.1.1.1 Materials Advisory Committee

The Materials Advisory Committee (MAC) should be made up of three to four senior materials managers from DOE, NASA, and/or DOE laboratories. These managers should be experienced with previous and ongoing nuclear and aerospace materials activities and should report directly to the SNP Program Manager. In this capacity, the MAC will be responsible for providing the SNP Project Office, specifically the Program Manager, with prioritized recommendations for initiation and/or continuation of specific materials technology activities. These priorities would be established on the basis of (1) meeting project goals and funding constraints, (2) avoiding duplication of activities, (3) ensuring the cost-effective utilization of all specialized facilities, and (4) establishing the method for providing a reference source of reliable materials properties information provided to the Project Office and systems design contractors. In addition, the MAC would be responsible for maintaining a summary of the delivery requirements and schedules for materials product forms needed to support subsystem and component testing activities throughout the SNP program and ensuring that appropriate actions are planned to meet these needs. The MAC would have oversight over the system used to develop materials specifications and inventory material product forms held by all program participants. It is anticipated that achievement of these objectives would require that the MAC meet initially on a quarterly basis.

VII.4.1.1.2 Materials Symposium

One of two critical tools in the effective management of the materials technology activity would be periodic SNP materials symposia. As near as possible to the initiation of the SNP program, an open symposium should be held with the purpose of (1)

inventorying the status of relevant SNP materials technology as advanced by previous and ongoing space nuclear and aerospace programs and (2) documenting the materials technology needs of the SNP program. These goals would be accomplished by forming small working groups composed of experts who will develop position papers describing the status and needs of their respective materials technology. The purpose of the initial symposium would be to ensure that SNP materials activities build on and fully utilize all existing materials technology information.

Additional materials symposia should be held on an annual basis. Attendees for the future symposium would be limited to SNP program participants. These follow-on symposia would serve as a forum for constructive criticism of ongoing materials activities and program office plans for new materials initiatives.

VII.4.1.1.3 Materials Properties Handbook

Availability of a reference set of materials properties data would serve a critical function during all phases of nuclear propulsion program evolution. In Phases I and II of the SNP program, the handbook would provide a reference set of preliminary materials properties information for system designers and the program office. During Phases I and II, competing system design concepts would utilize the same materials properties data allowing the program office to compare competing concepts on their system design merits. Use of a common data base would remove uncertainty regarding the degree of conservatism or optimization in the materials properties data used by different design contractors.

In Phase I, data in the materials handbook would be obtained primarily from previously published data and existing handbooks. The MAC would be responsible for establishing a process by which this data is reviewed to ensure its appropriateness to the SNP program. To assure the timely and cost-effective availability of the information, this review process cannot utilize large, cumbersome review committees. During Phases III and IV, the materials handbook would take on even greater importance. During these phases, the handbook would provide the consensus reference data used to design the system. Demonstration of the rigorous generation and review of this data by the SNP program will be required to obtain approval to operate the ground test reactor in Phase III and launch of the flight reactor in Phase IV.

VII.4.1.2 Work Requirements

On the basis of these proposed actions, a schedule for recommended management activities has been developed (Fig. 7-4).

The SNP program office should issue a charter for the MAC and appoint the members of this committee by the end of the first quarter of FY 1992. At this point, the MAC should meet every three to six months. One of the first actions of the MAC should be the preparation of a 5-year materials technology implementation plan. This implementation plan should describe the specific work to be performed in the materials technology task. This plan should utilize input from the program office regarding the SNP concepts to be pursued, concept selection dates, and material requirements for major component and subsystem tests. From this input, the 5-year plan should provide specific guidance on

- materials requirements and delivery dates,
- mechanical properties testing requirements,
- irradiation effects testing requirements, and
- coordination of materials specification throughout Phase I and II of the propulsion program.

The next task for the MAC would be the preparation of the charter and 5-year plan for the Materials Handbook task. By the end of FY 1992, the handbook task should issue a guide identifying the location of existing materials properties data relevant to the SNP program. This guide is expected to reference, among other documents, the old NERVA and MMW materials handbooks and the current SP-100 Project materials handbook. A materials handbook designed for the nuclear propulsion program should be issued by the end of FY 1993.

The materials symposium task would be performed on an accelerated schedule. The working groups for this meeting should be appointed by the end of FY 1991 with the meeting to be held in March of 1992. The proceedings of the meeting should be issued by the end of the first quarter of FY 1993. An annual symposium would be held in the third quarter of each subsequent year to support budget planning for future years.

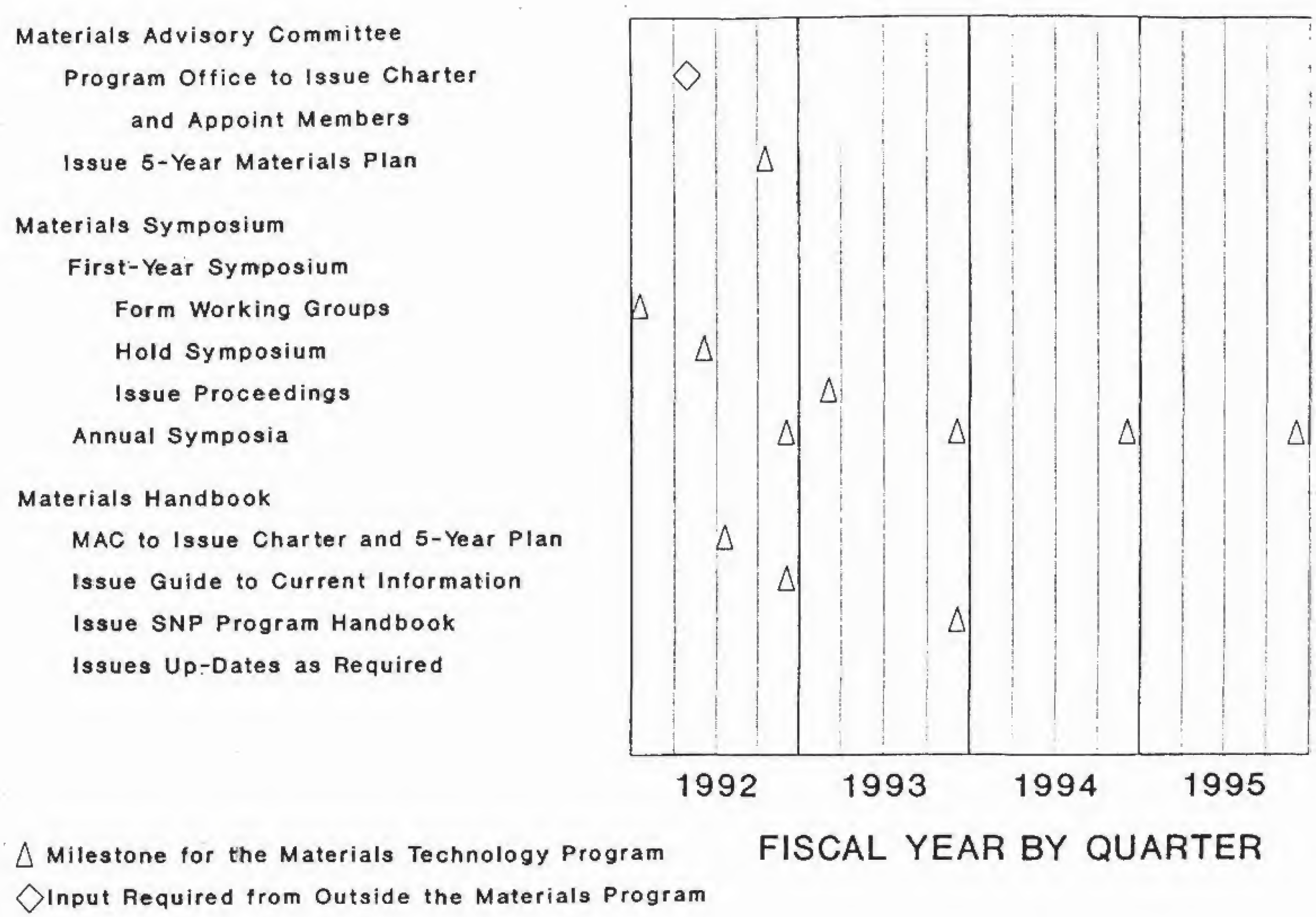


Fig. 7.4 Schedule of Recommended Management Activities

VII.4.2 **Alloys**

As indicated earlier, a variety of candidate alloys has been identified for specific applications in NEP and NTP concepts. Specifically, this activity would provide the technical initiatives necessary to (1) assess alloy feasibility issues associated with candidate metals and alloys for SNP concepts, (2) generate a technology data base sufficient to support the periodic material and concept selection decisions, and (3) allow for the initiation of a detailed engineering design of the SNP concepts selected in FY 1995.

VII.4.2.1 Technology Status of Candidate Alloys

The information that follows would provide a brief technology status of each candidate alloy or family of alloys and will highlight significant near-term technical issues.

VII.4.2.1.1 Refractory Alloys

A number of candidate refractory alloys have been identified for SNP applications.

Mo- and W-based alloys. These two alloy systems appear attractive for both NEP and NTP applications. On the basis of thermodynamic considerations and limited experimental data, both alloys systems should be compatible with alkali metals, circulating inert gas for Brayton-cycle systems, and hydrogen gas. Results from the earlier SNAP program and the SP-100 Project show that both alloy systems are compatible with UO_2 and UN fuel.

In the late 1960s and early 1970s, it was determined that Mo- and W-based alloys containing dilute additions of hafnium could be internally nitrided, and the resulting nitride dispersion provided the alloys with attractive creep strength properties at temperatures of 1500 to 1700 K. These alloys hold significant promise for NEP and NTP systems.

The improved low-temperature ductility and increased high-temperature strength of Mo- and W-based alloys containing dilute additions of rhenium were noted in the early 1970s. Work was briefly performed in the 1980s on Mo-7% Re alloys as part of the SP-100 Project. Currently, the thermionic program is evaluating the effects of HfC additions to W-based alloys for emitter applications. Early data suggests substantial

increases in the creep properties of the HfC-strengthened alloy at temperatures to 2000 K.

In the period from 1963 to 1970, extensive efforts were made to develop the technology base for complex tungsten thermionic emitters fabricated by chemical vapor deposition (CVD) methods. At present, the operational temperature limit for CVD-W emitters for continuous operations appears to be 1800 to 1900 K because of the limited creep strength of the CVD-W at these temperatures. Development of CVD methods to fabricate tungsten alloyed with rhenium or other strengthening additions may allow steady-state operation of thermionic emitters at temperatures significantly higher than is possible with CVD-W emitters.

In summary, the respective families of Mo- and W-based alloys are considered technically immature because there is little or no data available on the fabricability of these alloys into complex welded structural components, fuel and coolant compatibility, irradiation effects, and long-term thermal stability. Demonstration of the successful fabrication of these alloys into complex components is an immediate technical issue. The program should allocate 18 to 24 months for the delivery of industrially fabricated Mo- or W-based alloy sheet or tubular product forms needed to support subsystem and component testing activities.

Ta-based alloys. From the mid 1960s to 1973, Ta-based alloys were the reference structural alloy for the SNAP 50 and the NASA advanced lithium cooled reactors. At the onset of these programs, the reference material was the Ta-W-Re alloy T-111. These programs developed a mechanical property data base for these alloys adequate to support a conceptual system design. In addition, large and complex alkali metal loops systems were designed, fabricated, and successfully operated. The T-111 alloy is a commercial alloy available in a variety of product forms.

In an effort to improve the high-temperature creep properties of Ta-based alloys for space nuclear applications, development activities were initiated in the 1960s on Ta-W-Re-Hf-C alloys. These alloys used dispersion strengthening from HfC to achieve improved creep strength. One of these developmental alloys was ASTAR 811C. A substantial mechanical properties data base was developed for this alloy demonstrating excellent long-term load-carrying capability at temperatures to 1600 to 1700 K. Despite

the alloy's extensive mechanical and alkali-metal compatibility data base, ASTAR 811C should be considered a developmental alloy. The alloy is not routinely manufactured by industry, and 12 to 18 months would be required to obtain product forms needed to support SNP program testing activities. The compatibility of this alloy with reactor fuel and Brayton-cycle working fluids must be addressed immediately. For this alloy, additional effort is needed to optimize the fabrication of required product forms, characterize irradiation effects, and determine compatibility with candidate fuels and coolants. This alloy is a candidate for NEP applications only. Because Ta-based alloys are vulnerable to hydrogen embrittlement, this family of alloys cannot be considered as candidates for NTP applications.

Nb-based alloys. For high-temperature alkali-metal applications, the Nb-based alloy Nb-1Zr is the most technically mature alloy on the basis of the extensive use of this alloy for SNAP reactors in the 1960s and 1970s. Until recently, the Nb-1Zr alloy served as the baseline structural material for the SP-100 project. As a result, a substantial data base for this alloy has been generated. Nb-based alloys have been suggested as candidates for NEP Rankine-cycle concepts; however, their maximum high-temperature operating range is generally considered to be about 1300 to 1400 K for 7-year life applications due to creep strength limitations. Additional testing is immediately required to determine lifetime limits if this family of alloys is to be used for systems operating for 2 years in the 1500 to 1700 K temperature range.

In order to increase the creep strength properties of the Nb-1Zr alloy, consideration has been given to the addition of carbon and tungsten to the alloy. Although preliminary data show these additions strengthen the alloy, questions regarding the thermal stability and weldability of the resulting alloys remain unanswered. Resolution of these questions represent important feasibility issues. In addition, the compatibility of these alloys with Brayton-cycle working fluids must be determined. These alloys, like Ta-based alloys, are not considered compatible with high-temperature hydrogen.

Ti- and V-based alloys. The low density and high melting point of Ti- and V-based alloys relative to stainless steels and superalloys make them excellent candidates for 900 to 1200 K applications in NEP and NTP systems. More detailed data are needed on coolant compatibility and long-term strength properties. In general, adequate data

are available on these two families of alloys to assess their performance in conceptual SNP concepts.

Re-based alloys. Little or no alloy development has been performed on Re-based alloys; however, preliminary compatibility data suggest that rhenium alloys can tolerate hydrogen exposure at the temperatures proposed for NTP concepts. If the nuclear propulsion program pursues NTP concepts utilizing Re-based alloys, significant work must be initiated immediately to optimize fabrication methods and characterize hydrogen compatibility performance.

VII.4.2.1.2 Nickel-Based Alloys

A variety of nickel-based alloys, (Table VII-4) have been utilized in the NERVA/ROVER designs of the past and have been identified for use in some of the NTP concepts presented in the NTP workshop. Because these materials have been utilized in previous nuclear and aerospace applications, a significant technology data base exists. In general, extensive mechanical, fracture toughness, and crack growth rate properties data are available for most candidate nickel-based alloys. These data suggest that these materials should not be considered for multi-thousand-hour structural applications at temperatures greater than about 1250 K. Compatibility of the nickel-based alloys with hydrogen is an area of concern, and screening studies will be needed. The nickel-based alloys that appear as candidates for NTP applications do not present serious component fabrication concerns.

VII.4.2.1.3 Iron-Based Alloys

Alloys based on iron could be utilized for the reactor vessels, fuel tie rods, outlet nozzles, and turbine bearings. For many of these candidate materials, such as type 316 stainless steel and the superalloy A286, a substantial mechanical properties data base is available. This mechanical properties data base would suggest an upper temperature limit for these materials of approximately 1000 K. On the basis of previous experience with these materials, hydrogen compatibility is an area that will require evaluation. Fabrication of these alloys into components required for NTP applications is not expected to be an issue. In most cases, these alloys are commercially available.

VII.4.2.1.4 Aluminum- and Titanium-Based Alloys

These nonferrous alloy have been identified for NTP reactor pressure vessel application. For the aluminum-based alloys, a large mechanical properties data base is available and suggests these materials will be limited to applications having operating temperatures no greater than about 475 K. It is anticipated that testing to characterize the effects of hydrogen on mechanical properties of these alloys during cyclic temperature operation will be required. Experience with the fabrication of these alloys does not appear to be an area of significant concern at this time.

VII.4.2.2 Work Requirements

Specific activities required to resolve technical issues or characterize the materials sufficiently for their subsequent use in ground tests or flight application are described below.

VII.4.2.2.1 Alloy Development and Coordination

The objective of this task is to (1) provide coordination and direction to the evaluation tasks of individual candidate alloys or family of alloys; (2) provide periodic assessments to the MAC of alloy feasibility issues relative to candidate SNP concepts; (3) optimize composition, microstructure, and thermal-mechanical treatments of candidate alloys; (4) develop and qualify optimized alloy fabrication methods; (5) provide alloy product forms as required by the SNP program for technology activities associated with this and other technology elements; (6) characterize the weldability of candidate alloys; and (7) characterize the thermo-physical properties of the candidate alloys.

To meet these objectives, a lead organization should be identified to serve as the advocate for a family of alloys or, in some cases, a specific candidate alloy. Lead organizations would be responsible for coordinating technical evaluations and reporting on the development status of their respective alloy. Figure 7-5 provides a summary of recommended alloy development and coordination tasks for the FY-1992 to FY-1995 period. Initiation of this task requires the timely identification of the lead organizations by the program office. Further, the availability of industrially fabricated Ta-, W-, and Mo-based alloys could range from 12 to 24 months. Such long lead times could substantially delay the initiation of important subsystem and component tests.

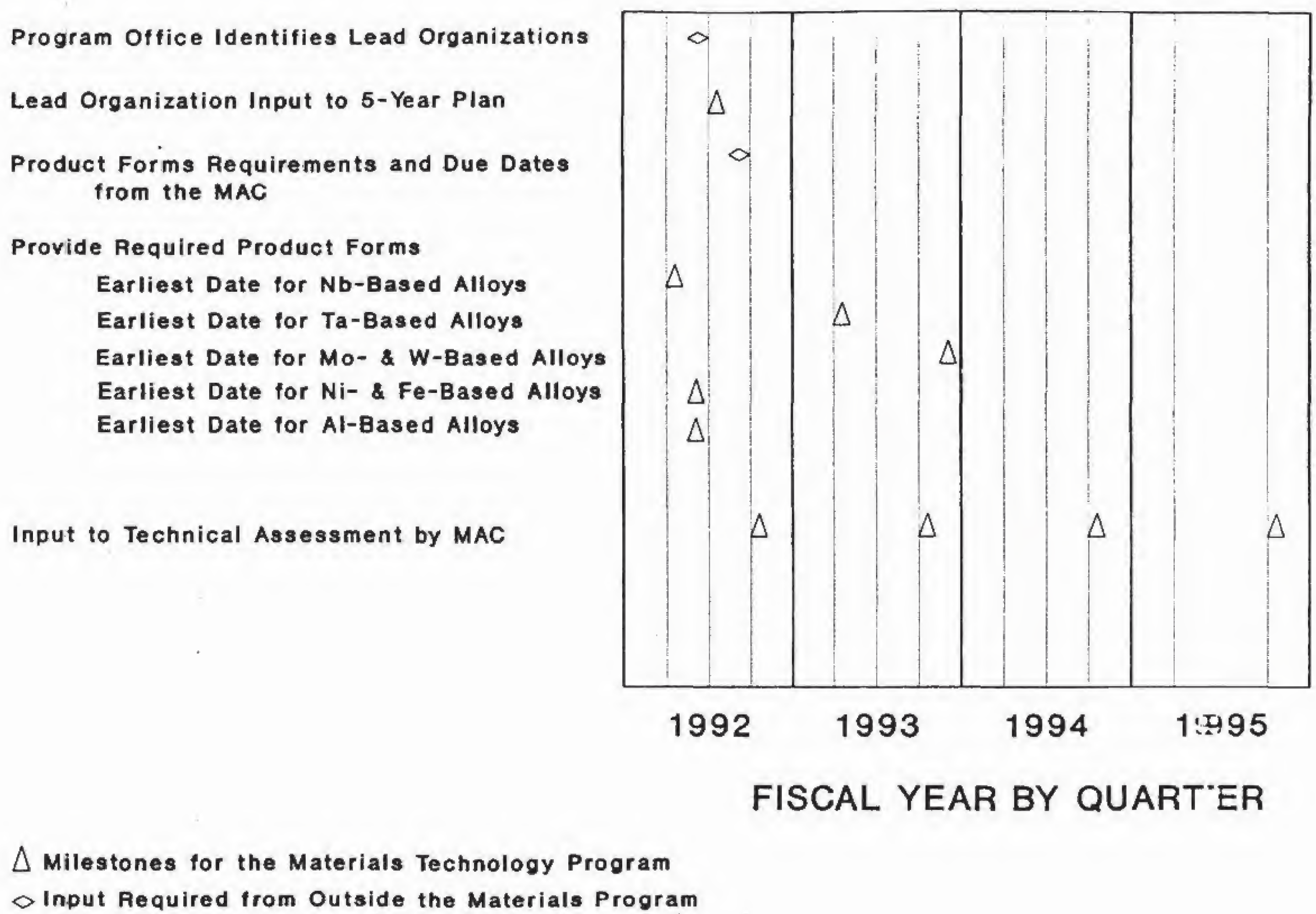


Fig. 7.5 Schedule for Recommended Alloy Development and Coordination

VII.4.2.2.2 Load-Carrying Properties

The objective of this task is to perform testing and analysis necessary to assess the load-carrying capability of candidate alloys. Although preliminary mechanical properties data currently available for candidate alloys may be adequate for their initial selection, additional high-temperature mechanical properties testing and analysis are needed to support the periodic material and concept selection decisions. These tests will require specialized facilities that may not exist or be available to the SNP program.

Compilation and evaluation. Previously published mechanical properties data and data generated by the nuclear propulsion program should be compiled and evaluated to aid in the alloy development activities and in alloy and concept selection decisions.

Uniaxial creep testing. Long-term tests at relatively low loads and high temperatures are needed to assess the load-carrying capability of candidate refractory alloys at prototypical conditions for NEP applications. Past experience dictates that creep testing of refractory alloys must be performed in specialized equipment capable of 10^{-9}-torr vacuum levels, and over a temperature range of 1300 to 2000 K. These facilities are available at ORNL, LLNL, NASA-Lewis Research Center, and Westinghouse, although many of these facilities are committed to the SP-100 Project.

Creep tests of candidate Ni-, Ti-, and Al-based alloys for durations of 10 to 50 h may be required for NTP applications. These tests would be performed in hot hydrogen at temperatures ranging from 500 to 1500 K. At this time, the availability of such facilities is not clear.

Biaxial tube creep tests. This testing method provides a less costly method of determining the high-temperature creep properties of refractory alloys under biaxial loading conditions. These testing methods do not appear to be applicable to materials for NTP applications.

Fatigue and creep-fatigue interaction. Because NEP concepts will be operated under a continuous load-following cycle and NTP concepts will be frequently cycled on and off, the response of candidate materials to high- and low-cycle loading must be assessed. For refractory alloys in NEP applications, fatigue testing must be performed in ultra-high-vacuum high-temperature test facilities. For materials considered for NTP applications, similar test must be performed in high-pressure high-temperature hydrogen

environments. A limited number of facilities exist and most are committed to the NASP program.

Fracture toughness. The potential for fatigue crack growth and brittle failure of candidate alloys should be determined at temperatures and conditions prototypical of ground transport of critical components and under expected launch and orbital-boost conditions. This is a critical issue for the Mo- and W-based alloys. Many materials considered for NTP applications realize reductions in their ductile-to-brittle transition temperature following exposure to hydrogen.

High-temperature tensile. Capability for characterization of the high-temperature tensile properties of both NEP and NTP structural materials will be required. For refractory alloys for NEP applications, temperature capabilities to 1750 K in a 10^{-7}-torr vacuum will be required. Adequate capability is thought to be in place.

Complex loading. Complex loading at elevated temperatures requires data from special tests to characterize elastic-plastic-creep interactions. Data for constitutive equations and structural validation are obtained from special tests such as stress relaxation, step-loaded creep, and uniaxial and biaxial non-isothermal creep and creep-rupture.

Summary. A summary of recommended activities in FY 1992 to 1995 associated with the alloy load-carrying properties characterization task is provided in Fig. 7-6. A major step in initiating the task is the development of a testing matrix. Such a matrix should identify the candidate materials to be tested and the specific testing conditions. This guidance is required to establish the number and type of test facilities required. It is anticipated that facilities appropriate for mechanical property testing of candidate materials for NEP and NTP applications could be on-line by the first quarter of FY 1993.

VII.4.2.2.3 Compatibility

The objective of this task is to determine the nature and extent of mechanical and physical degradation of candidate alloys with prototypical nuclear propulsion system environments. The long-term (> 10,000 h) compatibility of candidate alloys with alkali metal (liquids and vapor) and inert gases at the proposed NEP operating temperatures is not sufficiently known to gauge reliable performance of these materials. In addition, the compatibility of candidate alloys with cryogenic and hot hydrogen is not well

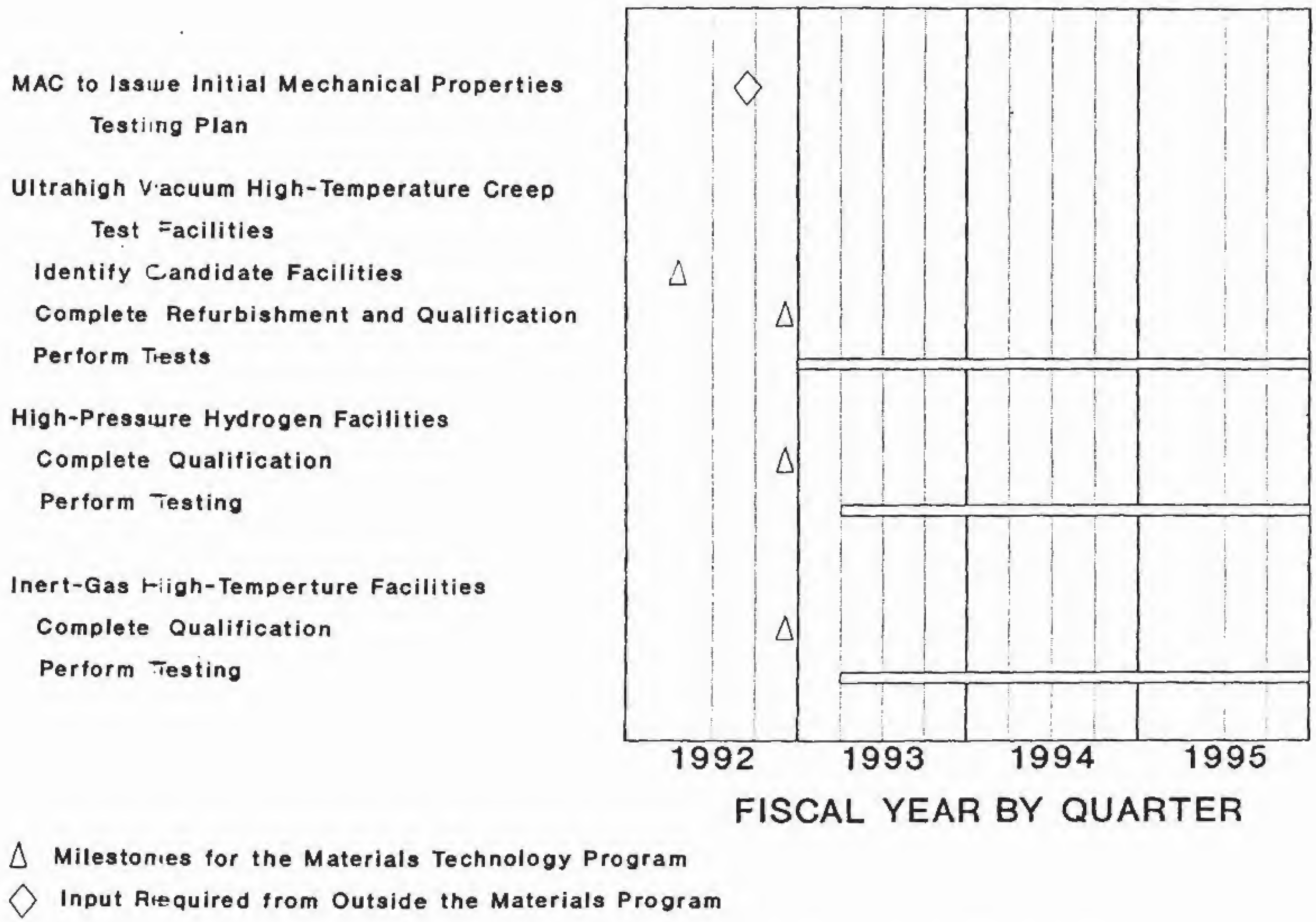


Fig. 7.6 Recommendations for Load Carrying Properties

C-3

defined. Resolution of these issues is critical to nuclear propulsion concept selection decisions. Recommended major activities associated with this task are summarized in Fig. 7-7.

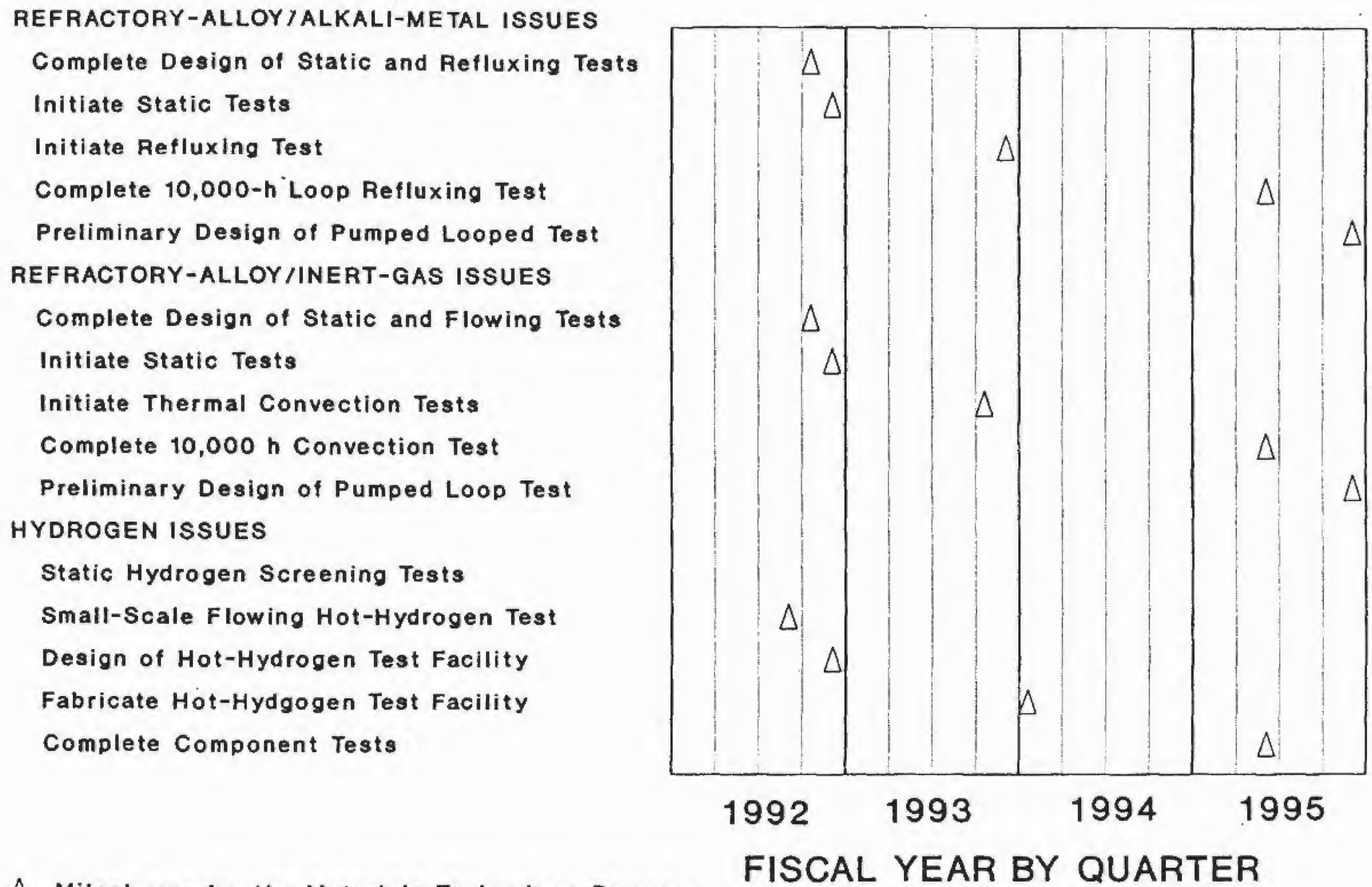
Inert-gas environment. A major feasibility issue associated with the operation of a power conversion system using inert gases and refractory alloys is the degradation of the alloys from the impurities in the gas and the mass transport of impurities from hotter to cooler alloy surfaces. To assess the relative compatibility of candidate refractory alloys for NEP Brayton-cycle applications, gas-metal reaction studies should be performed in vacuum and helium environments containing controlled concentrations of oxidizing and carburizing gaseous impurities. To assess the mass transport characteristics, small thermal convection tests should be performed. Results of these tests will enable designers to relate impurity effects and system operating parameters on materials performance. If a Brayton concept is selected for continued study in FY 1995, a forced-circulation inert-gas system should be fabricated and operated to obtain alloy compatibility data under prototypical conditions.

Alkali-metal environments. Candidate refractory alloys for NEP concepts should be evaluated in terms of purity, fabrication, and heat treatment requirements for service in molten and boiling alkali metals. In the period from FY 1992 to FY 1994, compatibility studies should be performed in static and refluxing capsules and thermal convection loops. If a Rankine-cycle concept is selected in the FY-1995 selection decision, a two-phase boiling-potassium loop should be fabricated and operated to provide long-term (>10,000 h) compatibility data for candidate fuel cladding, reactor structural, and turbine materials.

Hydrogen-gas environment. The response of candidate alloys in the hydrogen coolant proposed for use in NTP concepts must be assessed. This assessment should be performed by exposing candidate alloys to hydrogen at proposed operating temperatures and subsequently characterizing gas clean-up and the cool-down rates of the materials required to avoid embrittlement.

VII.4.2.2.4 Irradiation Effects

The objective of this task is to provide information on the effects of irradiation on candidate alloys and materials required for the materials and concept selection decision.



△ Milestones for the Materials Technology Program

◇ Input Required from Outside the Materials Program

Fig. 7.7 Schedule for Recommended Compatibility Studies

Property measurements should include swelling, irradiation creep, strength, and ductility. Postirradiation evaluation should include all properties mentioned above, plus determination of phase stability of the alloys. Irradiation effects on the properties of candidate high-temperature materials in the prototypical reactor environments is a feasibility issue. A summary of the recommended actions associated with this task in the FY-1992 to FY-1995 period is provided in Fig. 7-8. The pacing activity associated with this task is the completion of an assessment of the potential irradiation damage effects of candidate NTP materials. Further, the design of the irradiation experiment must be initiated by the third quarter of FY 1992 to ensure that PIE information on candidate materials is available in FY 1995 in time to support concept selection decisions.

VII.4.2.2.5 Component Fabrication

The objective of this task is the development of component fabrication technologies and nondestructive examination (NDE) methods required for the successful fabrication of refractory alloy components for SNP applications.

Although the capability for fabrication of components from Nb- and Ta-based alloys was demonstrated in the 1960s and 1970s, significant effort is required to recapture and advance this technology in support of the component fabrication and testing planned for the technology development phase of the SNP Program. A description of the specific activities associated with this task follows.

VII.4.3 Composites

The purpose of this activity is to develop advanced composite materials for reactor and non-reactor structural applications. This activity should provide the technical initiatives necessary to (1) assess feasibility issues for candidate composite systems, (2) generate a composite technology data base sufficient to support interim material and concept selection decisions, and (3) provide a sufficient data base to support the final concept and material selection decisions in FY 1995.

VII.4.3.1 Technology Status of Candidate Composites

Several innovative and developmental composites have been identified that offer the opportunity for improvements in SNP systems performance. These include metal-fiber/metal-matrix, ceramic-matrix, and carbon/carbon composites.

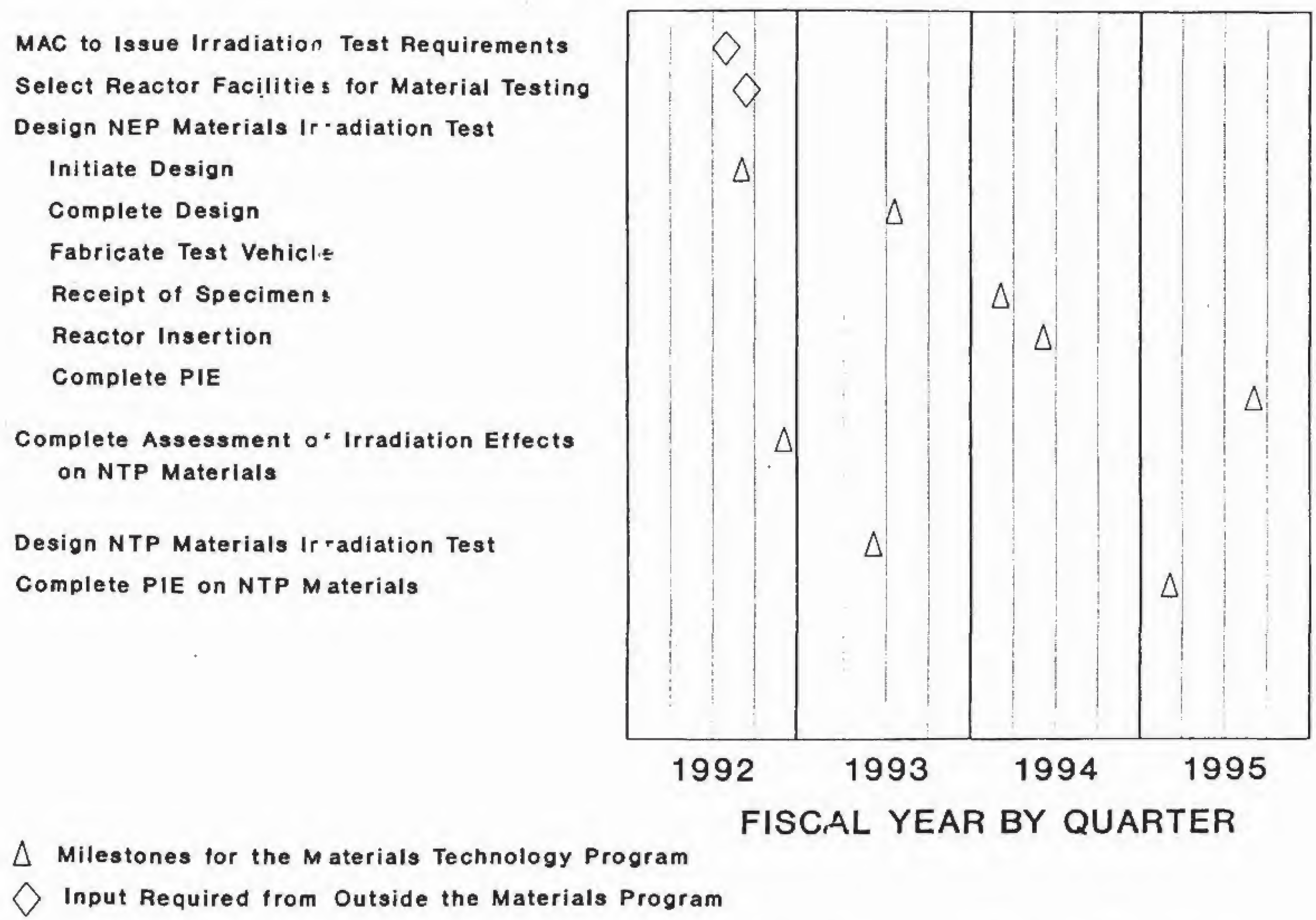


Fig. 7.8 Schedule for Recommended Irradiation Effects Testing

VII.4.3.1.1 Metal Fiber/Metal Matrix

The development of composite components composed of continuous high-strength W-alloy (W-HfC or W-Re-HfC) filaments in a niobium or Nb-alloy matrix is an innovative step in meeting the high-temperature structural materials requirements of proposed NEP thermionic and Rankine-cycle concepts. The basis for this technology advance is the extraordinary high-temperature strength and recrystallization resistance of W-based alloys and the excellent compatibility of the Nb-alloy matrix with the space environment and with the alkali-metal coolants and working fluids being considered for candidate NEP concepts. Work on this matrix composite system was performed in 1985 in support of the MMW Space Power Program.

Consideration has recently been given to W-HfC filament in a CVD-W matrix for thermionic emitter applications. Although the work appears promising, it has been delayed by the inability of industry to produce small-diameter W-HfC wire. This material could be used for in-core thermionic NEP concepts and NTP nozzle and fuel support applications.

VII.4.3.1.2 Ceramic Composites

Recent work on the development of ceramic whisker and continuous ceramic-filament-reinforced ceramic matrices have demonstrated that these materials can be fabricated with both high fracture toughness and high fracture strength at temperatures to 1600 K. This recent accomplishment makes this class of materials a new candidate for space nuclear power and propulsion applications relative to the material selections made for those systems designed in the 1960s and 1970s.

On the basis of these improved fracture toughness and strength properties, ceramic-matrix composites appear to be candidates for the hot flow path components for NEP Brayton-cycle systems and for the alternator housing for the Rankine-cycle generator. Both of those, as well as applications in NTP environments, were evaluated as part of the MMW Space Power Program in 1985. Specifically the following ceramic composites were evaluated:

- Al_2O_3 matrix Al_2O_3 reinforced,
- Al_2O_3 matrix SiC reinforced,
- ZrC matrix carbon reinforced,

- ZrC matrix SiC reinforced, and
- Si_3N_4 matrix SiC reinforced.

On the basis of this study, none of these composites appeared to be acceptable for NTP applications. However, only the Al_2O_3-reinforced Al_2O_3 and the carbon-fiber-reinforced ZrC should be considered for NEP Brayton-cycle applications while Al_2O_3-reinforced Al_2O_3, SiC-fiber-reinforced ZrC, and carbon-fiber-reinforced ZrC are candidates for NEP Rankine cycle applications.

VII.4.3.1.3 Carbon/Carbon Composites

Composites of carbon fibers in a carbon matrix (C/C), have many attractive attributes. These materials have the highest high-temperature strength and stiffness of any material. Carbon/carbon composites can be designed to have a specific thermal conductivity higher than such metallic conductors as copper and silver. Structurally, C/C is about 60% the mass of aluminum and has a thermal expansion of near zero.

Effective integration and advancement of current C/C composite technology will provide the opportunity for significant improvement in both NEP and NTP system performance. With regard to NEP systems, use of metal-lined C/C heat pipes for radiators can reduce the weight of NEP radiators systems by one-third. In addition, C/C composites are being considered for Brayton-cycle turbines. For NTP systems, the development of a coating to protect C/C composite from hot hydrogen could provide the opportunity to use this material for the turbine sections of the turbopump, the reactor pressure vessel, or the rocket nozzle. These applications could significantly increase system performance and reduce system mass.

Carbon/carbon composite technology is being utilized for rotating component applications in two areas. First, the Department of Defense (DOD) has developed C/C composites with diameters of approximately 25 cm for turbopumps and generator applications. These structures, consisting of 2-D and 3-D C/C composite structures attached to a metal hub, have been spun to 50,000 rpm. Second, DOD is designing and fabricating large-diameter (>24 cm diam) C/C composite rotors and stators for cruise missile engines.

Carbon/carbon composites are also being developed for both fusion energy and civilian reactor applications and are being considered as a fusion reactor plasma facing

material. For the latter function, the Fusion Program is determining the effects of neutron damage on C/C structures and characterizing the properties of candidate C/C composite materials. In addition, C/C composite materials are being developed for use in control rod applications for high-temperature gas-cooled reactors.

A number of important technical issues must be addressed to allow the use of C/C composites in SNP applications. (1) Coatings must be qualified to protect C/C radiators from atomic oxygen effects for NEP applications and to protect the materials from hot hydrogen in NTP applications. This activity is described in section 4.5 of this plan. (2) Processing technologies must be demonstrated to support the fabrication of large and reliable rotating equipment for NEP applications and for large complex structures such as NTP pressure vessels and exit nozzles. (3) Methodology for the reliable prediction of structural properties for material utilizing different fiber architectures and fabrication methods must be validated.

VII.4.3.2 Work Requirements

VII.4.3.2.1 Metal Fiber/Metal Matrix

The objectives of the metal-fiber/metal-matrix composite tasks are to (1) provide coordination and direction to the needed development activities, (2) provide periodic assessments of feasibility issues relative to candidate SNP concepts applications, (3) demonstrate the feasibility of the candidate composite fabrication methods, (4) provide product forms as required for technology activities associated with this and other technology elements, (5) develop and characterize joining methods, (6) characterize the physical and load-carrying properties, (7) assess the effect of neutron irradiation, and (8) provide component design integration.

The major focus of this task is the development of a technology data base necessary to demonstrate the potential of metal-fiber/metal-matrix composite for SNP applications. The development and assessment of this technology should be performed in four subtasks. The major deliverable from these tasks should be an assessment of the performance of this class of material through the testing activities described below. These inputs should be a significant factor in the decision to continue work on this material beyond FY 1995. A summary of the recommended activities associated with this material is provided in Fig. 7-9.

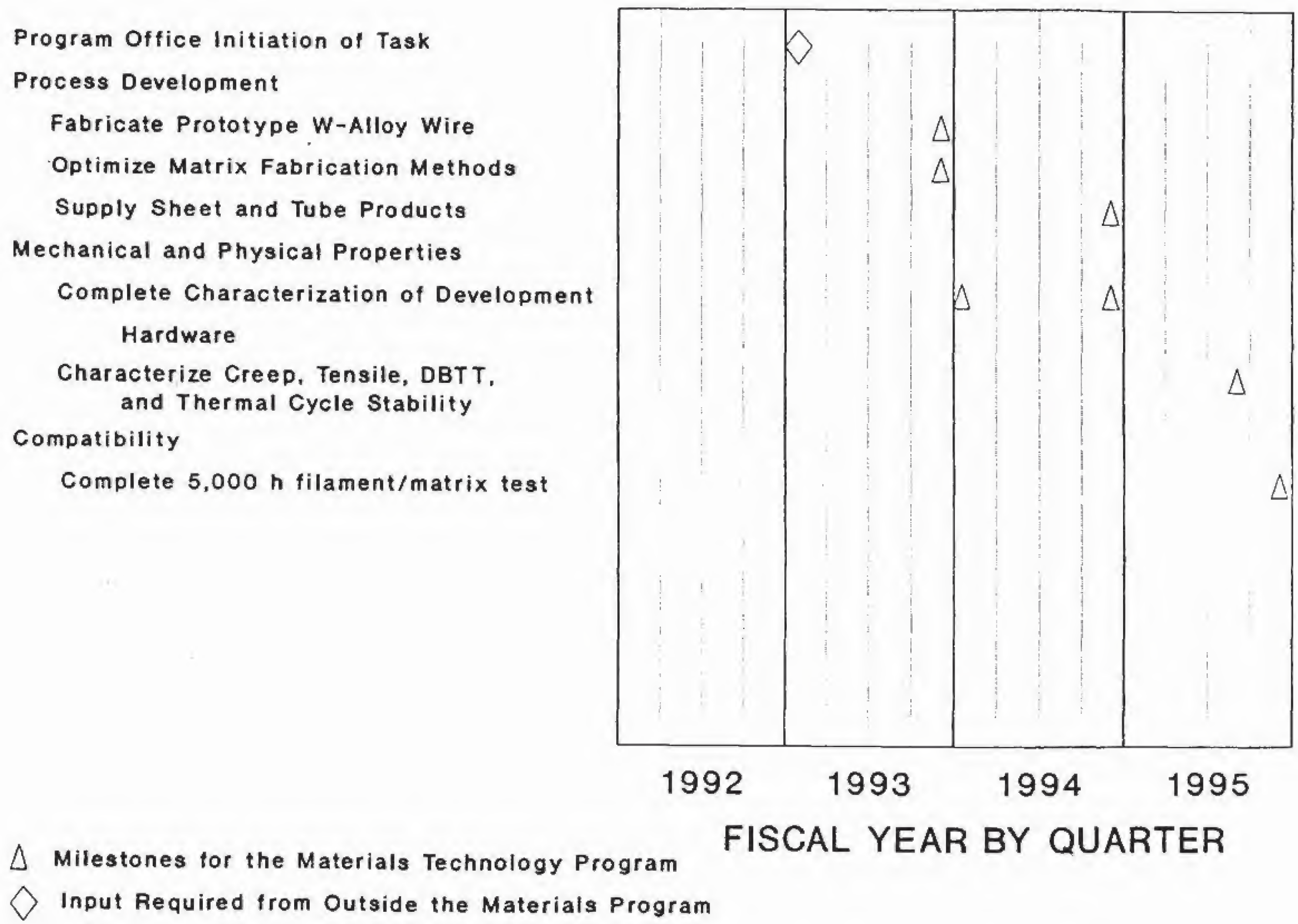


Fig. 7.9 Recommended Metal-Matrix Technology Plan

Process development studies. The objectives of this task are to (1) demonstrate the feasibility of cost-effective manufacturing of W-4Re-0.35HfC or W-0.35HfC fine wire and fabricating metal-matrix tungsten-metal-fiber composites and (2) provide the materials hardware needed to support materials and component testing of this matrix material.

For planning purposes, it has been assumed that this task does not begin until FY 1993. Goals for FY 1993 are the successful demonstration of the fabrication of fine W-HfC wire and the optimization of the fabrication method for metal-matrix composites using lamp filament as the tungsten wire. Sheet and tubular specimens should be fabricated in FY 1994 to support other materials and component testing activities.

Mechanical and physical properties. The major emphasis of this subtask should be the determination of mechanical properties and an assessment of the thermal-mechanical stability of the composite as determined by response to imposed thermal cyclic conditions. In FY 1995, using prototypic materials, efforts to characterize the creep, tensile, and ductile-to-brittle transition temperature (DBTT) should be conducted. In addition, thermal cycling testing should be performed to assess the stability of the filament to matrix interface during anticipated NEP and NTP thermal cycles.

Compatibility. Two compatibility issues must be addressed for this materials system. The first is the compatibility of the metal filament with the metal matrix at the proposed SNP operating temperatures and lifetimes. The second is the compatibility of these materials with proposed NEP and NTP working fluids and coolants. Before the materials and concept selection decision scheduled for the end of FY 1995, only the issue of filament/matrix compatibility can be addressed. If this major feasibility test is successful, these metal-matrix composites could be included in large alkali metal, inert gas, or hydrogen tests that would be performed in FY 1996 or later.

Irradiation Effects. A major consideration in assessing the performance of this class of materials is their irradiation damage tolerance. It is unlikely this important issue can be addressed before the materials and concept selection decision date. Specimens for such a test could be provided in FY 1994. Results from the PIE of these specimens from irradiation tests simulating NEP conditions would not be available until FY 1996. However, results of tests simulating NTP conditions could be available in FY 1995.

VII.4.3.2.2 Ceramic Matrix Composites

The objectives of this task are to (1) provide coordination and direction to the ceramic-matrix-composite development activities, (2) provide necessary assessments of ceramic-matrix-composite feasibility issues relative to candidate SNP concepts, (3) identify ceramic-matrix systems suitable to SNP needs, (4) develop the leading candidate ceramic-matrix composites (including qualifying their fabrication processes and generating the property data bases for these advanced materials necessary for component design), and (5) provide ceramic matrix composite product forms as required for technology activities associated with this and other technology elements.

Activities performed in this task will provide only cursory technical information needed for preliminary material and concept selection decisions scheduled for FY 1995. Activities have been organized into three subtasks: (1) process and fabrication development, (2) mechanical and physical properties, and (3) compatibility. A summary of recommended major milestones associated with these three subtasks is provided in Fig. 7-10.

Processing and fabrication development. The major focus of this subtask is to (1) identify optimum ceramic matrix composite systems for critical SNP components applications and (2) demonstrate that these composites can be fabricated into required SNP prototypical component shapes. Ceramic matrix composite systems to be initially evaluated should include both whisker- and long-fiber reinforcements in ceramic matrices.

In FY 1992, the only activity associated with this subtask should be the preparation of a critical assessment identifying the leading candidate ceramic-matrix composite(s) for NEP and NTP application. The assessment should identify a "prototype shape" which would be used as the basis for all subsequent ceramic-matrix-composite fabrication development in this task. No activity on other subtasks could be started until FY 1993. In FY 1993, work on ceramic-matrix-composite processing targeted at the prototype shape should be initiated with the objective of identifying a fabrication process that could yield a prototype shape having a microstructural uniformity. Material from the fabrication process yielding the prototype shape would be used in both the mechanical/physical properties and compatibility subtasks.

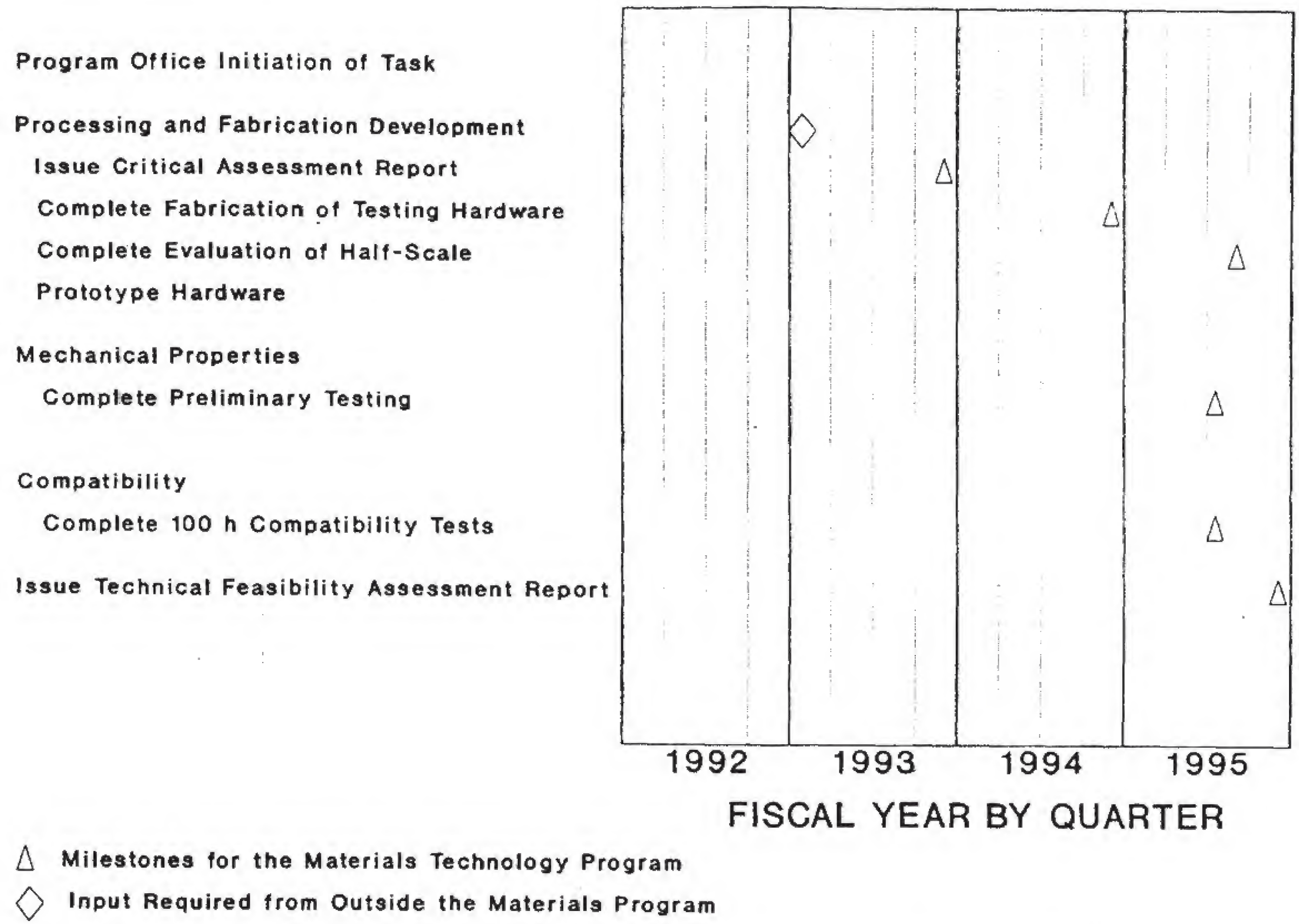


Fig. 7.10 Schedule for Recommended Ceramic-Matrix Composite Development

Mechanical and physical properties. On the basis of the recommendation from the critical assessment developed in the processing and fabrication development subtask, mechanical properties activities will begin in FY 1995. Initial focus will be on stress-strain relationships as a function of temperature performed initially in dry nitrogen. If the ceramic-matrix-composites are included in one of the SNP concepts selected in FY 1995, extensive measurements of stress-strain, creep, and fatigue should be initiated in FY 1996. These tests would be performed in prototypic environments.

Compatibility. Work on this subtask should not be initiated until FY 1994. Initial activities would utilize relatively numerous small specimens treated to 100-h exposures to Brayton- and Rankine-cycle environments.

VII.4.3.2.3 Carbon/Carbon Composites

The objectives of this task are to (1) provide coordination and direction to the C/C composite development activities, (2) provide periodic assessments of C/C composite feasibility issues relative to candidate SNP concepts, (3) develop and demonstrate innovative fabrication techniques using improved matrix and fiber materials, (4) develop destructive and nondestructive techniques required for product qualification, (5) provide C/C composite product forms as required for technology activities associated with this and other technology elements, and (6) characterize the thermomechanical and chemical properties of C/C composites.

A multiphase program is required to prepare C/C composites for use in space nuclear propulsion systems.

Technology Assessment. Complete an in-depth assessment of (1) the program needs, (2) the state of the art for C/C materials including properties, testing, understanding of component sizes and fiber architectures, and (3) process technology including capacity, sizes, science in-and-on-process quality assurance. As part of the materials symposium, appropriate ongoing C/C programs should be reviewed for technology applicable to space nuclear propulsion. Commercial capabilities would be inventoried, and potential collaboration with industry would be assessed.

Design Methods. The purpose of this subtask is to assemble the best available design methods and life prediction models for C/C in both nuclear and non-nuclear environments. The focus should emphasize thin, large-area C/C structures and shapes

similar to the expected needs for NTP pressure vessels and nozzle hardware. The milestones of this phase would be models for predicting performance and failure in various fiber architectures (2-D and 3-D). This effort would continue to support the design effort for specific hardware and would interact with the processing and manufacturing effort to ensure that designs are producible.

This subtask would be performed largely in parallel with the design methods subtask and would be oriented toward an in-depth evaluation of processing techniques and development of the science required to produce high-performance C/C hardware. This subtask should focus on developing processing systems and procedures that would be transferrable to large-scale equipment operated by commercial producers. The program should focus on developing a real-time, knowledge base for processing controls that provide for on- or in-process quality controls and certification. Milestones would include demonstration of 1/4- to 1/2-scale models of the components for a system demonstration of processing controls and validation of the reproducibility of the processing methods. To accomplish this phase, an advanced processing capability should be established.

This capability should be a laboratory research and development facility focused on advancing the understanding of the relationship between process variables microstructure. Emphasis should be placed on significantly improving material reproducibility, improving interlaminar properties, and reducing processing cost. This capability should also be used to fabricate specimens for exploratory test and evaluation to support design methods development and to produce parts of adequate size to demonstrate scaling as full-scale hardware is designed.

VII.4.4 Ceramics

The purpose of this activity is the development of high-temperature ceramics for reactor and non-reactor structural applications. This activity would provide the technical initiative necessary to (1) assess feasibility issues for candidate ceramics associated with proposed SNP concepts, (2) generate a ceramic technology data base sufficient to support the interim material and concept selection decisions, and (3) provide the technology data required for final concept and material selection in FY 1995.

VII.4.4.1 Technology Status of Monolithic Candidate Ceramics

The information that follows will provide a brief technology status of selected ceramics that appear to be candidates for SNP applications. This section will attempt to identify near-term technical issues and indicate if work is ongoing to address those technical issues that are relevant to SNP applications.

VII.4.4.1.1 Alumina and Beryllia

Ceramic materials have a critical role in the NEP Rankine-cycle systems. Specifically, ceramics are required to isolate the alternator stator from the potassium working fluid. The work on these materials should provide the properties required for selection and design of a full-scale housing and also should include substantial work on the process required to fabricate a prototype housing.

The alternator housing required for NEP Rankine-cycles is expected to be larger than the currently identified manufacturing capability for either alumina or beryllia ceramics. Further, little is known regarding the behavior of these ceramics under applied stress in a hot potassium environment. Acquiring this data should be a high priority for the materials program.

In addition, the technology for joining the ceramic alternator must be developed and demonstrated for the joint sizes consistent with NEP system designs. Preliminary results obtained in the 1960s included good results for small samples using rapid brazing cycles. Major difficulties were encountered when the joints were scaled to the size required for 100-kW(e) Rankine-cycle power systems. These problems were due, at least partially, to a lack of understanding and control of the thermal expansion differences between the ceramic, the brazing alloys, and the refractory alloy components of the joints. These problems have not been solved, and they will be even more severe than in the 100-kW(e) size joints because of the much larger size of the alternator components required in the megawatt power systems needed for the NEP concepts. The demonstration of high-reliability joints between the candidate ceramics—alumina and beryllia—and refractory alloys of a prototype size for NEP systems and in a hot potassium environment is also a major objective of this work.

VII.4.4.1.2 Thermionic Insulation

Thermionic sheath insulator performance is one of the major life-limiting factors in the in-core thermionic concept and can also limit the maximum operating voltage. The environment in which the sheath insulator operates is unprecedented in its severity in terms of the combination of temperature and radiation and electric fields. Alumina, which was the standard in early programs, may be limited to a lifetime of 3 to 4 years because of radiation effects. These technical issues are currently being addressed in the Thermionic Fuel Element (TFE) Program.

VII.4.4.1.3 Absorber and Reactivity Control Materials

Reactivity control materials—reflectors and absorbers—with the worth and ability to withstand long-term irradiation at proposed NEP or NTP operating temperatures have not been qualified. The current state of the art for control materials that have a relevance to the SNP program are the Liquid Metal Fast Breeder Reactor, HTGR, and SP-100 reactor programs. Control materials evaluated by those respective programs hold promise for meeting the requirements. However, the ability of these materials to tolerate the thermal shock associated with NTP operation, to remain chemically stable in the proposed NTP and NEP operating environments, and to resist irradiation damage during these conditions remains an uncertainty.

The approach to reactor control for SNP systems could involve in-core control rods typical of Liquid Metal Reactor (LMR) and HTGR designs, reflector controls typical of SNAP, NERVA/ROVER, and SP-100 designs or combinations of in-core and reflector control components. The control strategy will influence selection of specific materials which have the appropriate combination of nuclear properties, physical properties, chemical stability, and irradiation stability.

Control materials technology for LMR and HTGR applications provide a base for assessing in-core application. Boron carbide (B_4C) is the material for which the greatest experience is available through the LMR. This material has been incorporated also in boronated graphite in HTGR control rods. Neutronic worth to weight consideration suggests B_4C as a prime candidate for SNP in-core control systems. Other materials which receive consideration, but have received only minor development support from the LMR program are the rare earth compounds Eu_2O_3, EuB_6, and metallic tantalum.

Operating conditions for the LMR include temperatures hundreds of degrees K lower than NEP goals; and therefore LMR use stainless steel rather than refractory metal cladding, and use sodium rather than lithium coolant. Compatibility of candidate absorber materials with cladding materials and the effect of possible contact with the NEP coolants are obvious feasibility issues. Many of these issues are being addressed by the SP-100 Project.

The transients imposed during the rapid start-up of NTP systems raise questions regarding the mechanical stability of control materials. For example, B_4C will contain helium from neutron captures at low power operation but release the helium at some unknown rate during transient operation. Swelling of this material during steady-state operation is reasonably well characterized, but the effects of rapid temperature and neutron reaction rate increases are unknown. Uncertainty also exists regarding the mechanical response to thermal stresses in such transient compounds.

Neutron reflector applications, such as rotating drums outside the core in the SP-100 and NERVA/ROVER concepts, are based on use of beryllium metal or BeO. Refractory compounds of beryllium may be required for dimensional stability in the high-temperature environments. Little development work for reactor applications has been done on these materials. Enhanced thermal conductivity and strength of such compounds as Be_2C could be advantageous where reflectors are part of the controls for reactors.

VII.4.4.1.4 Other Ceramic Candidates

A number of ceramic materials hold the potential for application in SNP systems, but have not been specifically called out in concepts presented at the SNP workshops. A review of the status of some of these candidate follows.

Silicon Nitride and Silicon Carbide. These ceramics could be candidates for structural application in the hot flow path of advanced Brayton cycles and NTP concepts. Major concerns about these materials are the critical flaw sensitivity, the limited fabrication technology relative to the size of components needed for SNP applications, and a limited long-term mechanical property data base. The applications of these materials for similar applications is being evaluated as part of the Advanced Gas Turbine Program funded by DOE.

Zirconium Carbide and Niobium Carbide. Zirconium carbide was identified in particle bed concepts associated with NEP and NTP applications. For these and ROVER systems, ZrC and NbC/ZrC were to serve as a neutron moderator and a structural support. Major feasibility issues exist regarding the use of ZrC as a core support and are associated with the fabrication of ZrC into complex configuration. Further, it is uncertain if this material can tolerate the thermal stress associated with NTP operations.

VII.4.4.2 Work Requirements

Specific activities required to resolve technical issues or sufficiently characterize the materials for the subsequent use in ground test or flight applications are described below.

VII.4.4.2.1 Aluminum Oxide and Beryllium Oxide

The objectives of this task are to (1) provide the planning, coordination, and direction required for NEP Rankine-cycle systems for oxide ceramic alternator housing; (2) determine the optimum fabrication method for high-reliability cylindrical shapes from these ceramics; (3) develop data for the electrical and mechanical properties of these materials in a Rankine cycle environment; and (4) develop technology for joining the large ceramic alternator reliably to a refractory alloy structure. No activities have been planned in FY 1992; however, if SNP program plans call for the ground operation of a potassium-driven Rankine-cycle conversion system in the FY 1996 time frame, activity to resolve these technical issues must be initiated in FY 1993. These activities have been organized into three subtasks; (1) processing; (2) mechanical properties; and (3) compatibility. Specific milestones recommended for this task are summarized in Fig. 7-11.

Processing. Efforts should be initiated in FY 1993 to evaluate fabrication methods for making either alumina or beryllia closed-end cylinders approximately half the size required for the flight version of the Rankine-cycle NEP system. It is anticipated that fabrication of a half-size system could be demonstrated by FY 1994.

Mechanical Properties. Principal mechanical properties determined for these ceramics should include fast fracture strength in four-point flexure, Weibull modulus, and fatigue strength. Testing in FY 1994 should be performed in hot inert gases, with preliminary tests performed in hot potassium in FY 1995.

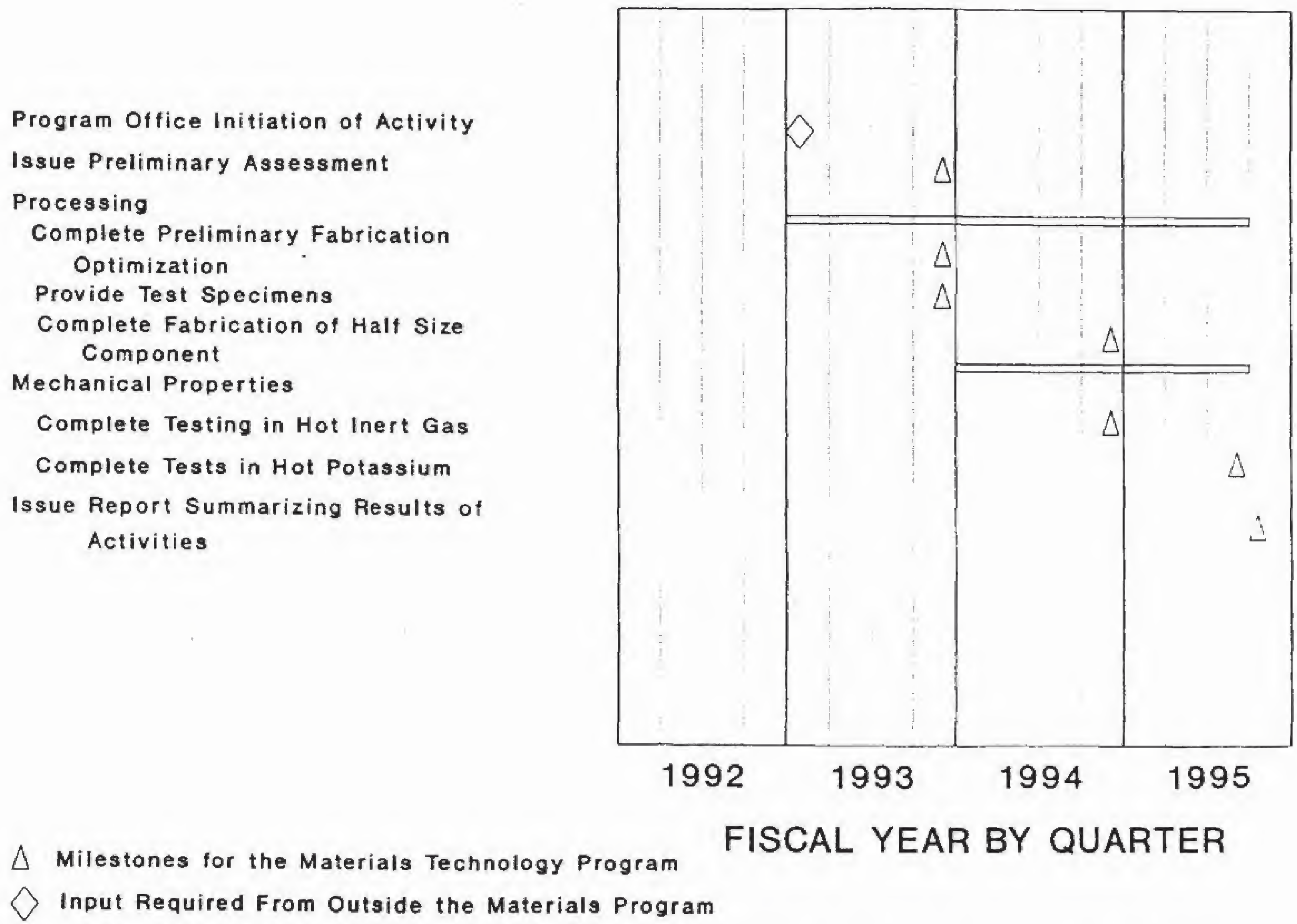


Fig. 7.11 Summary of Recommended Plan for Aluminum Oxide and Beryllium Oxide

Compatibility. Compatibility studies to determine the stability of the candidate oxide ceramic compositions in the Rankine-cycle environment are needed. These studies would include microstructural and microcompositional analyses of specimens following exposure to the hot potassium. Preliminary tests of commercially available materials should be performed in FY 1994 with prototypic materials being tested in FY 1995.

VII.4.4.2.2 Absorber and Reactivity Control Materials

The objective of this activity is to provide coordination and direction in the development of absorber and reactivity control materials. Specific technical objectives are to (1) assess the feasibility of fabrication of candidate control materials, (2) evaluate the chemical compatibility with prototypical environments, and (3) characterize the effect of neutron irradiation.

Following the selection of candidate materials, basic screening tests should be performed to evaluate the compatibility of these materials with cladding and coolants, thermal-mechanical stability, and tolerance to neutron irradiation effects. The activities to select and qualify reactivity control materials will be integrated with the requirements of the neutronics and controls program element and of the irradiation test vehicles developed for the materials and fuels program element. Detail on the activities associated with absorber and reflector controls materials development are provided below, while a summary of recommended major milestones and events is provided in Fig. 7-12.

Selection and evaluation. This task should provide focus to the completion and evaluation of previously published data on candidate control materials and should evaluate recent technical information. The existing technology data for control materials should be compiled and evaluated in FY 1994. On the basis of this analysis and the determination of the control material requirements by the neutronic and control element, candidate control materials could be identified. An assessment of control material feasibility issues should be issued to aid in materials and concept selection decisions. Acquisition of the needed technology data base for candidate materials should be prepared on the basis of laboratory and in-reactor testing starting in FY 1996.

Fabrication. This task provides specimens of candidate control materials for compatibility, property, and irradiation tests. Candidate materials should be procured

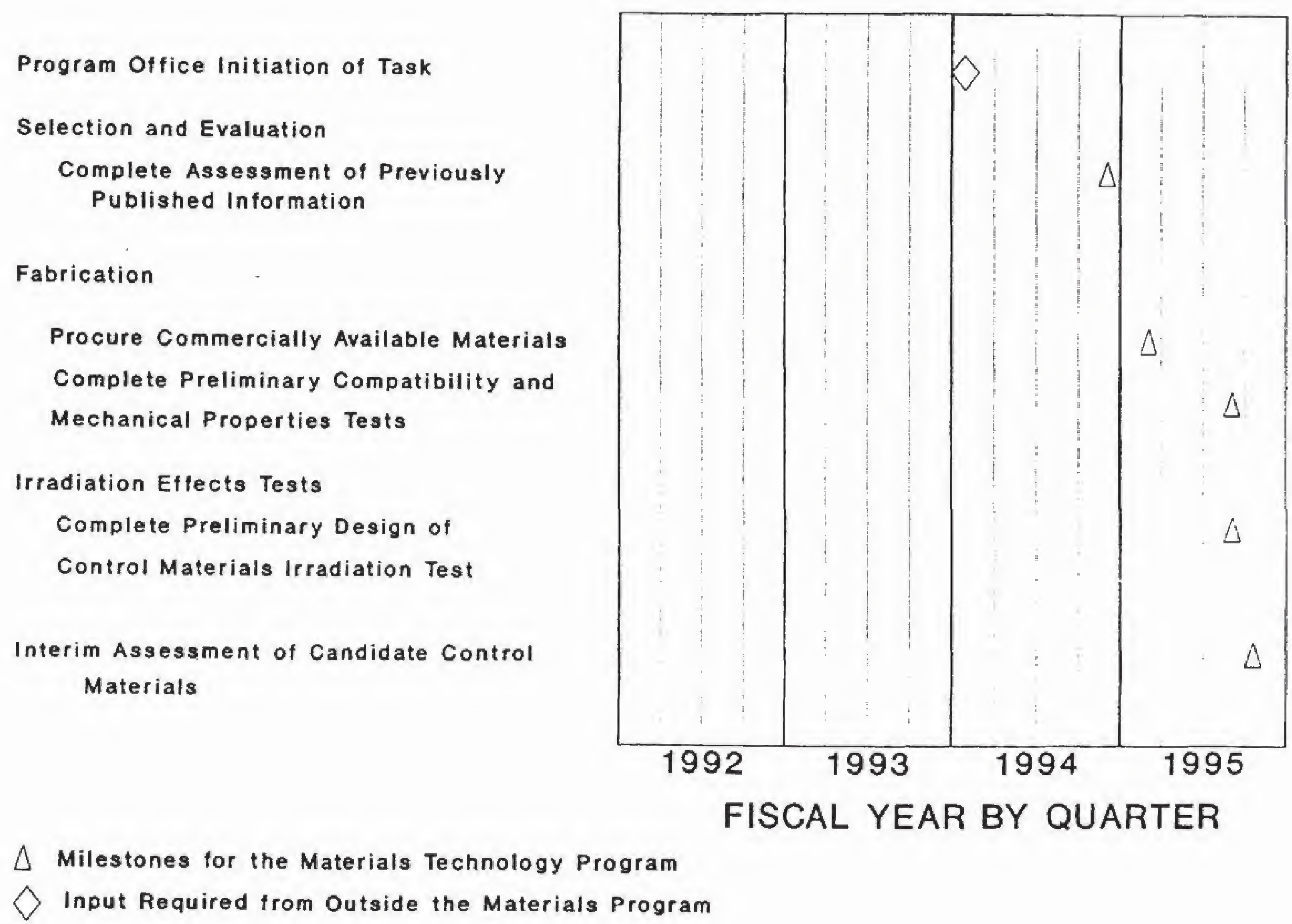


Fig. 7.12 Recommendations for Absorber and Reactivity Control Materials

commercially where possible; however, some materials may require fabrication development, which would dictate preparation by using laboratory equipment. Starting in FY 1993, fabrication methods for candidate materials should be assessed, and laboratory fabrication equipment identified and plans for refurbishment of this equipment made if necessary. Candidate materials should be procured or fabricated in the laboratory as required to support testing activities needed to acquire engineering data starting in FY 1996.

Compatibility and property testing. The compatibility of candidate control materials with cladding and coolants should be assessed. In addition, mechanical and physical properties of candidate materials should be characterized and included in the assessment provided to the SNP Program Office in 1995.

Irradiation effects. Irradiation testing of candidate materials must be performed to assess the dimensional stability and the material integrity and property changes of candidate materials at proposed reactor operating conditions. Effects of prior irradiation on material behavior in NTP start modes must be evaluated.

Review of previously published irradiation effects information should be performed in FY 1994 and included in the assessment report. If control materials are selected for SNP application that have not been characterized as part of the SP-100 Project, preparation of irradiation effects specimens should be initiated in FY 1996.

VII.4.4.2.3 Other Ceramics

At this time, little or no design base exists for any of the candidate NEP and NTP concepts. However, it is clear that a number of ceramic materials not previously identified in this report, will serve critical functions within these systems. These ceramic materials and their important functions can be identified as the level of maturity of the candidate SNP system increase. The purpose of this task is to provide general support in the evaluation of candidate ceramic materials as they are identified during the evolution of the program.

VII.4.5 <u>Coatings</u>

The purpose of this activity is the development of specialized coating required for both NEP and NTP applications. New coating technologies will be required for a variety of applications to resolve technical problems that could have significant impact on the

lifetime and reliability of candidate nuclear propulsion systems. These applications include: coatings for thermionic emitters that will significantly reduce the electron work function, and in turn, substantially improve the performance of thermionic systems; tribological coatings to prevent the galling or rapid wearing of moving high temperature surfaces; and protective coatings required to protect structural materials from hostile environments. Note that the coatings for NTP fuels are considered an integral part of the fuels development activity. In each of these applications, this activity will provide the technical initiative necessary to (1) assess feasibility issues for candidate coating systems, (2) generate a coatings technology data base sufficient to support the materials and concept selection decisions planned for FY 1995, and (3) provide the technology data and processing experience necessary to support the design and fabrication of components and subsystems.

VII.4.5.1 Technology Status of Candidate Coatings Systems

The information that follows will provide a brief technology review of the coatings systems that appear to be candidates for SNP applications. This section, as with other technology sections, will attempt to identify near-term technical issues and indicate if work is ongoing to address these issues.

VII.4.5.1.1 Coating to Protect Carbon/Carbon Composites

The protection of the C/C pressure vessel and nozzle from attack by hydrogen at operating temperatures presents a problem not much different than that of oxidation protection of C/C. The issues involve providing an outer surface composition to the component that resists attack and remains crack free through repeated thermal cycling. This can be a difficult problem because the coefficient of thermal expansion (CTE) for C/C is near zero, causing stress in protective coatings that have nonzero CTE values. In addition, the refractory materials available to protect C/C are typically brittle ceramics or metals, which accommodate little strain before cracking.

A method that has been successfully used to overcome the brittle nature of protective ceramic coatings has been to codeposit a second phase, producing a dispersed-phase composite coating. As in composite ceramics in general, the result is a material with greater toughness that can withstand the stresses caused by CTE mismatch and protect C/C. Such a system developed by the NASP program was

demonstrated to protect C/C from oxidation in static air under repeated cycling to 1370 C. Another potential approach is to produce C/C components by chemical vapor infiltration in which the outer volume of material has a hydrogen-resistant phase substituted for the carbon.

A potential program for developing a hydrogen protection system for C/C components would contain four phases: (1) thermochemical and literature assessment, (2) experimental screening of potential systems, (3) scale-up to representative components, and (4) qualification of the system.

Thermochemical and literature assessment (Year 1). A variety of potential C/C materials should be thermochemically assessed with regard to their stability in hydrogen at the proposed temperatures. Materials such as ZrC and NbC have achieved some success as coatings under the ROVER program. These materials should be investigated, along with materials such as HfC and TaC which have been reported to be relatively stable in hydrogen. Other systems for which the literature appears promising can be identified regardless of thermochemical stability in hydrogen.

System development and screening tests (Years 2-4). A set of coating or infiltration systems which appear promising based on the assessments would be chosen for screening tests. Single and multiphase coatings with appropriate CTE values chosen to result in stresses below the threshold at which cracking should occur should be prepared. In addition, CVI C/C would be produced with protective phases infiltrated into the outer volumes. These systems should be evaluated in flowing hydrogen at representative temperatures.

Partial-scale part development and evaluation (Years 5-6). Materials systems that survive the screening evaluation should be produced as partial-scale components. Thus scale-up development will be required to allow reliable production of the protected C/C. Evaluation under proposed operating conditions would be required.

Qualification (Years 7-8). Full-scale hardware should be produced for system qualification.

VII.5 SUMMARY AND RECOMMENDATIONS

This materials plan is the product of the Fuels and Materials Panel's efforts to review the candidate NEP and NTP concepts, identify classes of materials that may be

required for all major systems associated with these concepts, and determine major materials technology issues. These activities have led to a number of broad observations.

1. Performance goals for proposed NEP and NTP systems are beyond current materials technology.
2. Issues regarding materials performance are diverse and are expected to have significant impact on all major subsystems and components.
3. On the basis of a cursory review of the NEP and NTP systems, approximately 100 different materials have been identified as potential candidates.
4. As initially conceived, materials technology development is not a unique line activity in the program plan; nor is there a management focal point for the coordination of the anticipated materials development activities required for this program.

From these observations, a number of specific recommendations relative to the implementation of an effective materials activity have been developed. Decisive action is needed relative to the management of the materials activity to ensure that material technology solutions are developed in a cost-effective and timely manner. Three specific recommendations were developed:

1. A Management Advisory Committee should be created from a small number of senior materials managers from DOE, DOD, and NASA organizations. This committee should have oversight of all materials activities throughout the SNP program and report to the Nuclear Propulsion Program Manager. The committee should periodically assess the effectiveness of ongoing materials work, make recommendations regarding new initiatives, and ensure that methods are in place for the effective analysis and dissemination of materials information to both government and industrial participants.
2. A symposium of materials experts should be held in FY 1992. The purpose of the symposium would be to recapture the materials technology of the past space nuclear power and propulsion programs and to obtain consensus agreement on the materials technology needs of the currently proposed nuclear propulsion program.

3. A materials handbook would be developed and issued to program participants. Initially this handbook would summarize previously published and relevant materials properties information. Additional data generated subsequently by the program would be included in later versions of the handbook to fill existing information voids. The handbook would serve a critical role early in the program by providing a common source of information from which industrial designers could base their designs and program management could compare competing concepts' systems on their design merits. Later in the program, the handbook and its data approval process would serve a critical role in the process required to obtain approval to operate an nuclear propulsion nuclear system on the ground or to obtain approval to launch the integrated system.

From an analysis of the materials technology needs, several important long lead activities have been identified:

1. Identification of the candidate refractory alloys for NEP applications should be made as soon as possible to allow start of the process of procurement of industrially fabricated product forms such as sheet, plate, and tubing. These product forms are required to support technology activities associated with the development of fuel, power conversion, and thermal management systems. On the basis of experience with the SP-100 Project, 12 to 24 months may be required for delivery of these materials.
2. Design and preparation of irradiation experiments for NEP and NTP materials should be initiated. For practically all of the candidate materials, little or no irradiation effects data is available at anticipated NEP and NTP operating temperatures, neutron fluences, and/or environments. Activities should be initiated in FY 1992 to ensure that postirradiation effects information will be available by FY 1995 to support concept and material selection decisions to be made at that time.
3. The design and preparation of materials compatibility tests should be started. Relative to NEP concepts, relative uncertainty exists regarding the compatibility of refractory alloys with the impurities associated with Brayton-cycle working fluids and the compatibility of some candidate alloys with Rankine-cycle working fluids. With regard to NTP systems, the tolerance of candidate structural materials with

hydrogen has not been adequately characterized. Because these activities would require delivery of specialized material product forms (requiring possibly 24 months) and fabrication and operation of complex test loops, activities should be initiated in FY 1992 to ensure that feasibility issues associated with materials compatibility be resolved by FY 1995.

This plan also revealed the need to develop and qualify several innovative new materials systems in order to achieve the performance goals of the SNP program:

1. Carbon/carbon composites hold the promise of significantly lowering the system mass and increasing the operating temperature for several key NEP and NTP subsystems. Unfortunately, neither a technology nor manufacturing base exist to support the application of carbon/carbon composites for these nuclear propulsion SNP applications. The initiation of this long-lead innovative effort holds the promise of significantly improving the performance of nuclear propulsion systems.
2. To support the use of carbon/carbon composites for NTP applications, hydrogen-resistant coatings are required. The coatings need to be impermeable to hydrogen at high temperatures.

As a concluding remark, the Fuels and Materials Panel's deliberations led to the development of the following statement of regarding the relative importance of fuels development and materials development.

- Achievement of NTP system performance goals require the development and qualification of a new, innovative, high-temperature reactor fuel system. On completion of significant qualification activities, existing materials could be used to support the NTP system; however, use of these materials in combination with the new fuel technology will not allow realization of the full performance potential of the NTP system. New and innovative materials technology must be developed and used in combination with a new fuel system to achieve the lowest system mass and greatest system impulse power.
- Achievement of NEP system performance goals could be met with existing fuels technology; however, existing structural materials technology is not adequately in hand to support this system. Qualification of the structural materials required in all major NEP subsystems is expected to be the longest lead technical activity and

will likely pace the implementation of the selected NEP system. The incremental fuels development needed to meet the longer term NEP requirements (described in Section VI) can be undertaken in the time necessary for NEP materials development.

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VIII. OTHER REACTOR TECHNOLOGY DEVELOPMENT

The fuels and materials technologies are clearly going to be the longest lead items in the development of reactors for nuclear propulsion. However, the other reactor technologies also require significant advances from the current state-of-the-art and plans for development of these technologies need to be prepared. The present panel was unable to do this in any detail because of time limitations. However, a start was made in some of these areas and the initial ideas are included here for completeness.

The primary other reactor related technologies are:

- Instrumentation
- Control
- Neutronics
- Thermal Hydraulics
- Structures

Development is required in all areas. We note that concept focal points identified several of these as key issues for their concept development, as evidenced by their entries in the tables in Appendix D.

VIII.1 Instrumentation and Control

Development of an effective and reliable nuclear rocket capability for the space exploration program requires instrumentation for monitoring fuels and materials tests and for controlling the rockets. The testing applications are less complicated, since all components of the instrumentation system except the sensors are accessible during the test and need not be radiation hardened. However, sensors are not now available and must be developed to operate at temperatures >2000 K for periods of months and surviving neutron fluences up to about 10^{20} n/cm^2 with negligible or predictable drift. In contrast, sensors for the control of nuclear rockets require not only the high temperature and high fluence capabilities of the test instruments, but also life-times as long as 10 years with low drift and high reliability. The signal

processors for rocket control must operate unattended and must experience gamma doses that substantially exceed present capabilities or incur large shielding penalties.

Instrumentation for Fuels and Materials Testing

In the next few years, some improvements must be made in instrumentation to perform high-temperature irradiation testing of fuels and materials for the Nuclear Electric Propulsion (NEP) or Nuclear Thermal Propulsion (NTP) rockets. Requirements for the temperatures, life-times, and fluences for several candidate fuels are given in Table VIII 1

Table VIII-1 Operational and Testing Temperatures For NEP and NTP Fuels

System		Operational			Testing		
		Temp (K)	Time (hr)	Fluence (nvt)	Temp (K)	Time (hr)	Fluence (nvt)
NEP							
UO_2 Centerline		2300					
UO_2 Clad		800					
UN Cermets	min				1400	720	$>3\times10^{20}$
	max				2200	34,500	$>1\times10^{22}$
Categorizing Criteria		$\geq$ 2500	>10	4×10^{18}			
NTP							
UO_2 Cermets	min	2800			2500	0.2	$>7\times10^{16}$
	max				3600	720	$>3\times10^{20}$
SP-100		1700	>61,000	2×10^{22}			
Categorizing Criteria		$\geq$1500	>61,000	2×10^{22}			

Fluences for the SEI fuels and materials irradiation tests assume a flux of 10^{14} nv. Heretofore, fuel irradiation tests have been performed for the LMFBR and the HTGR reactor programs in the DOE test reactors at ORNL at temperatures up to about 2500 K for times up to about 4000 hr with neutron fluxes of 10^{14} -10^{15} n cm^{-2} s^{-1}. In these tests, temperatures indicated by W-Re thermocouples drifted several hundred degrees kelvins at irradiation temperatures of about 1800 K; ultrasonic thermometers were even worse, with only Johnson noise thermometers providing reasonably accurate temperatures for periods of thousands of hours and neutron fluences

approaching 10^{22} nvt. Optical thermometry has not been used in nuclear fuel irradiation tests, but would be required at temperatures greater than about 2800 K if the methods could be adapted to fuel irradiation capsule requirements for containment. In some tests, neutron fluences of $\geq 10^{21}$ nvt have been survived by low cross-section refractory metal sensors. Chemical compatibility between fuels, capsules, and thermometers will limit the temperature and time that such experiments can be performed to not much more than a few thousand hours. A materials property that limits the high temperature use of thermocouples, resistance thermometers, and possibly the Johnson noise thermometer, is the loss of resistance of oxide insulators at temperatures above about 1300 K, which causes shunting of the electrical output and thus, a temperature error. The ultrasonic thermometer does not share this limitation and has been used at temperatures as high as 2700 K, but it is sensitive to mechanical interference. Additional development should be directed toward the use of radiation pyrometry coupled with fiber optics or single-crystal light pipes to measure temperatures greater than about 2500 K for fuels and materials testing.

Other instruments for fuels and materials testing include pressure gauges and strain gauges. NaK-coupled capillary pressure gauges have been qualified by the Energy Technology Engineering Center (ETEC) for use in LMFBRs at temperatures up to about 900 K and are now being developed for service at 1400 K for the SP-100. High-temperature strain gauges have also been developed and used in fuel tests at temperatures > 900 K

Instrumentation for Nuclear Rocket Control

As noted above, instrumentation for nuclear rocket control, including some aspects of ground testing, requires substantial improvement over the existing technology used for fuels and materials testing. These capabilities stem from the mission requirements which include: (1) unattended operation with no maintenance, (2) high reliability, (3) extended life - as long as ten years, (4) significant gamma doses to solid-state signal processors, and (5) ambient temperatures ranging from ~100 K to 300 K. The types of instruments to be qualified for rocket control extend

from all the conventional process instruments – temperature, pressure, flow, level, etc. – to flux monitors, actuator sensors, and leak detectors. [Not included in this assessment, but in need of further development, are the sensors and controls for maintaining habitability in manned rockets.] The operational requirements for the two rocket propulsion systems were presented in Table II-3 of Section II of this report.

The instrumentation for the NTP and NEP rockets must be considered as integral parts of the control system that includes entire instrument channels and actuator channels connecting the system to be controlled with the controller. The components that comprise the instrument channels and the actuator channels are shown in Figure VIII.2. This figure identifies the need for sensors, signal processors, transmitters, cables, multiplexers, converters, and actuators that will meet the environmental conditions in a nuclear rocket application. In addition, the hardware and software for the main controller and its related interfaces for command, safety, and diagnostics must be developed and qualified.

The NEP or NTP control system differs from most commercial reactor control systems in that it will probably be digital, it must minimize failures, it will operate autonomously and unattended, it must respond rapidly to anticipated and unanticipated events, and it is subject to mass, volume, and power restrictions. On interplanetary missions, there will be no time for the nuclear rocket to wait for command instructions to be radioed from Earth-based stations. Some development may be needed to adapt modern signal processor design ideas to the reliability levels needed for nuclear rockets. Multiplexers in particular may play a key role rocket control system design since they offer major reductions in wire and cable loads. They may be implemented with optical fibers, but if so, electrical-to-optical (e/o) signal converters would be needed near the sensors and again near the actuators. These locations would impose large gamma fields on the converters which are beyond the state of current technology. Fiber optic technology could reduce cable weights and EMI pickup, if the technology can be developed to overcome radiation effects on the cables ("darkening") and provide e/o and o/e signal converters that can withstand radiation damage. In addition to the bleaching of cables by heating them and the possibilities of developing radiation-resistant liquid-core fibers, another solution to the

Table VIII-2 Recommended NEP and NTP I&C Component Development

SENSORS	
Temperature	Flow Meters
Thermocouples	Venturi (dP)
Resistance Thermometers	Electromagnetic (EM & PM)
Johnson Noise Thermometers	Target
Radiation Pyrometers (non-contact)	Vortex Shedding
Fluorescent Laser Pulse (non-contact)	
Ultrasonic Thermometers	
Pressure	Level
Force Balance (Direct coupled)	Float
Capillary Coupled	J-tube
Differential Pressure	Ultrasonic (non-invasive)
	Inductive (non-invasive)
	Gamma Transmission (non-invasive)
Position/Displacement	Vibration/ Seismic
LVDT for CRD Position	High-Temperature Strain Gauges
Angular position indicators	
Inductive and other Valve Position Indicators	
Leak Detection	Flux Monitors
Alkali Metal Ionization Detectors	LLFM Source-Range Detectors
Conductance Gauges	Wide Range Fission Counters
	Compensated Ion Chambers
	Special Cosmic Particle Detectors
	In-Core Flux Monitors (SPNDs or Gamma Thermometers)
SIGNAL PROCESSORS	**SIGNAL TRANSMITTERS**
EMF/Temp Converters	Fiber-Optic e/o Converters
RTD Bridge Converters	Optical/Electric o/e Signal Converters
Noise Thermometer Preamplifier	Analog/Digital Signal Multiplexers
dP Pressure/Flow Converters	Digital Signal Demultiplexers
Ultrasonic Driver/Receivers	
Flux Monitor Preamplifiers	
Wide Range Single Mode Flux Monitor	
CONTROL SYSTEM COMPONENTS	**ACTUATORS**
Programmable Logic Controllers	Control Rod Drives
Dedicated Microprocessors	Valve Drives (pneumatic, electric, et al.)
Actuator Drivers	
Buffers & Isolators	

cable darkening problem is the use of digitally coded signals that are not affected by signal attenuation, but that approach depends on improved radiation resistance of analog-to-digital (a/d) signal processors.

Development Plan

The major limitations on our present abilities to realize such a control system for nuclear rockets are the lack of process and flux sensors qualified to temperatures >1400 K and the sensitivity of solid-state digital (or analog) signal processors to gamma radiation dose and environmental temperature extremes. If provisions are made for shielding electronics to gamma doses less than 10 MRad and cooling the electronics to temperatures between 300 and 327 K, existing electronic components and designs might be used. However, the mass and volume penalties would be significant. Without added shielding, gamma doses up to 300 MRad are expected in the 10-year SP-100 mission. Existing programs at Sandia National Laboratories for the SP-100 program are demonstrating the possibilities for extending the gamma tolerance of electronics by improvements in materials and design of semiconductor devices and by redesign of the electronic circuits to minimize the effects of device degradation. Two orders of magnitude improvement over existing technology is required. Instrument and control equipment on some flight vehicles may reach the 600-1100 K range which far exceeds conventional semiconductor device tolerance. Substantial technology development investment would be required to produce high-temperature electronic components, which has been the subject of programs in the past with limited success. Temperature control of the SP-100 multiplexer cabinet is already included in the design by necessity .

Sensors for process control and flux monitoring in the NEP and NTP rockets that are qualified to operate at temperatures >1400 K require, in some cases, new sensing concepts to allow material's limits to be exceeded, but in most cases, the sensors need only be redesigned to use more refractory materials. As with thermocouples, many electrical sensors (pressure gauges, level detectors, etc.) are subject to loss of accuracy at temperature above 1300 K where metal oxide insulators begin conducting. Some design modifications may minimize the electrical leakage

problem, but particular attention should be paid to non-contact or non-invasive sensors (such as inductive flow meters or level detectors) that do not require the sensing element to be in contact and at the same temperature as the working system. In particular, high sensitivity flux monitors used for startup monitoring do not need to operate at the fuel or coolant temperatures, since they can sense the neutron flux remotely.

The particular sensor task that faces the NTP and NEP program is to provide a complete assortment of instruments, which have been qualified by testing for nuclear service, that will cover the expected ranges of measured parameters, and are backed by an assured, qualified industrial source-of-supply. Only by use of such an instrument catalog can the nuclear designer select and specify instruments which will allow the nuclear rockets to be operated. This process of selection, qualification, and supply assurance traditionally has taken 3-8 years for nuclear instrumentation in applications that were much less stringent than nuclear propulsion requires.

Controllers for nuclear rockets must be designed to accept signals from process sensors, receive commands from mission leaders, and transmit signals to actuators (control rod positioners, valves, etc.) The application of recent developments in smart sensor/smart actuator could improve the reliability of these control functions. More attention needs to be paid to fault avoidance or fault tolerance (robustness) than in commercial power plants where the reactor protections system is (presumably) always there to shut down the reactor if safe limits are exceeded. There are situations where scramming a nuclear rocket is <u>not</u> the safe thing to do, such as those encountered in naval reactor applications! New modes of control have been developed that can readily be implemented in an automated digital control system but would have been difficult in convectional hard-wired analog systems. These control modes must be programmed into the hardware selected for the controller with the appropriate software. The controller system – hardware and software – must be validated and verified, including tests for unintended function, and the system simulated to explore as many possible operational scenarios as possible. Procedures, facilities, and some tools are available to perform these design tasks, but still require several years to initiate and complete. The plan to develop and implement a digital control system

must consider and accommodate the evolution and obsolescence of computer technology that will surely occur over the next decade while the nuclear rocket program approaches lift off.

A list of instrumentation and controls components which must be developed, tested, qualified and a source of supply assured includes those in Table VIII-2. The information is for illustrative purposes only and is be no means complete.

The Compilation of Development Issues in Section IV of this report showed I&C issues ranking in the top 20 as: Instrumented Fuel Element Tests, Neutronics and Control, Rad-Hard High-Temp Electronics, and High-Temperature Thermometry. The fuels development schedule presented in Section VI requires the development of high temperature thermometry for instrumented fuel element tests starting in 1995 that would meet the 2500 K, 10-hr requirements for NTP fuels and the 1500 K, 7-year requirements for NEP fuels. The mounting of a ground test of a nuclear rocket in the first decade of the new century, i.e within 15 years, would require an imminent start of the I&C development, qualification, and source of supply assurance program for either propulsion concept. Capabilities to execute a successful program of instrumentation and control technology development, qualification, and source-of-supply assurance, already exists at the DOE National Laboratories. These capabilities include experienced personnel and existing high temperature and/or liquid metal testing facilities.

If I&C development activities cannot all be undertaken immediately, then the following priorities are suggested to accommodate the short-term needs for fuels and materials testing, mid-term needs for simulation and ground testing of nuclear propulsion systems, and longer term applications to flight systems:

Thermometry for Fuels and Materials Tests,

Other Sensors (if any) for Fuels and Materials Tests,

Rad-Hard Electronic Devices and Systems Tests,

Process and Flux Sensors for Ground Testing and Flight Systems,

Signal Processors, Converters, and Transmitters for Flight Systems, and

Central Processor Hardware, Software, and Simulators for Flight Systems.

In summary, instrumentation and control development for the NEP and NTP. nuclear rockets should be undertaken at the start of the program, not left as an after thought. Successful I&C technology directs and allows the vehicle to perform its mission. Instrument qualification takes a long time! Drift and irradiation effects studies require years. Some new instruments need research and development to meet the higher temperature levels in the nuclear rockets. The availability of a qualified complement of instruments and control system designs would allow the system designers to make best choices early in the program.

VIII.2 Neutronics

In the area of neutronics there are several areas that require development to ensure that the core designs are optimum, the static and dynamic control conditions are completely understood, and the heat source and radiation sources are accurately computed. Significant advances in design computational methodologies have helped bring the technology up to its present advanced level. The following additional requirements are necessary.

- Cross-section Measurement and Evaluations: Neutron interaction cross-sections are needed for a number of isotopes for which the cross-sections are poorly known. Examples are Re, Ta, Mo. In addition, since the NTP systems operate at different temperature regimes than conventional reactors there is a need to determine the cross-section both at very low temperatures (when cold hydrogen first enters the reactor) and very high temperatures. These data have both operational and safety implications.
- Code Development and Validation. Continuous energy and multi-group Monte Carlo codes and deterministic transport theory codes have been reasonably well established for design and neutronics analyses. However, there are several other required design related analyses that are required that need methods development. Prominent among these are reactor space-time kinetics codes. The codes need to be validated for application to the new cores.
- Critical Experiments. As is customary for all new reactor development, a set of "zero" power critical experiments will need to be performed to verify the

adequacy of the methods and data being used and, eventually to produce bias factors for design optimization. In addition, a large number of kinetics and safety parameters can be directly measured. These will help immensely in the safety evaluations and reviews. Note that the nuclear "furnace" will very probably require its own critical experiment. The Facilities Panel has included critical experiment facilities in its list of required facilities.

VIII.3 Thermal Hydraulics

The proposed gas cooled and liquid metal (LM) cooled solid core reactors pose complex thermal hydraulics problems. Development and validation of analysis codes is necessary to have confidence in reactor behavior under operating conditions. This will require the performance of experiments ranging from simple geometry basic measurements to extract fundamental data and correlations to near-prototypic geometry measurements to verify flow and thermal conditions. For LMR's, microgravity experiments might be necessary.

For advanced propulsion systems, the thermal hydraulics problem might be even more critical and require detailed testing.

In summary, the Panel believes that there are significant technology development requirements with reactor technologies other than fuels and materials. Planning for these should be started in FY92 to ensure that balanced reactor development can take place.

IX. FUELS AND MATERIALS REQUIREMENTS FOR ADVANCED PROPULSION CONCEPTS

As part of the effort by the Nuclear Thermal Propulsion Technology Panel, a subpanel was formed to examine advanced or innovative propulsion concepts. By agreement, the term "innovative" referred to non-solid cores. Two exceptions included were the Foil Reactor Concept and the Fission Product Drive. The methodology and findings of the subpanel are detailed in the NTP Technology Panel report. One aspect of the subpanel effort, however, was to identify critical issues pertinent to materials requirements for the innovative concepts. While no attempt was made to produce a detailed development plan for the fuels and materials for advanced concepts, a brief section on the top level issues is included here for completeness.

In general, the driving motivation for examining innovative concepts is to increase the specific impulse of the engine to values greater than 2000 s. To accomplish this feat, the operating exhaust temperatures of the propellant must exceed 10,000 K. Thus, the primary materials impact is governed by the need to contain and channel gases at such extreme temperatures. In addition, the injection, handling, and recovery of uranium-based fuels at such temperatures are critical issues for some concepts. Furthermore, most of the concepts examined produced an extreme radiation environment so that material behavior under high radiation fluences was identified as another general issue. The high temperature instability of solid fuels is avoided in several of these concepts by using fuel in the liquid or gaseous state. Thus, the fuel integrity problem inherent in solid core concepts is transformed to a fuel confinement and storage problem. For the fusion and the antiproton propulsion systems, of course a whole different class of "fuels" is required.

Each of the concepts contained certain material issues and requirements. A listing of these is pertinent to the scope of this report. A list of the concepts and the specific issues are shown in Table IX.1. It needs to be emphasized that this is not a comprehensive list, but a result of a quick assessment. Certain system aspects can be seen as common from this table. Clearly, a nozzle wall material must be found that

TABLE IX.1 SPECIFIC ISSUES FOR INNOVATIVE CONCEPTS

CONCEPT	COMPONENT	ISSUES
Gas Core Reactors (open)	Nozzle	High Temperature H_2 Embrittlement Transpiration Cooling Fission Product Chemistry
	Chamber Wall	Transpiration Cooling H_2 Embrittlement Radiation Damage High Temperature
Gas Core (closed)	Containment Window	Optically Transparent High Temperature Radiation Damage Resistant Thermal Stress Fuel Storage and Handling
Fusion	Chamber Wall	Radiation Damage Magnetic Field Interactions Cooling
Antiproton	Chamber Wall	High Energy Radiation Resistant Magnetic Field Interactions Cooling Storage
Explosive Drivers	First Wall	Extreme Radiation Damage Flexibility Lightweight Sails Abundance of Nuclear Pulse Drivers
Foil Reactor		Thin Uranium Based Foils Erosion and Radiation Resistant
Liquid Annular Core	Chamber Wall	Liquid Uranium Resistant Thermal Gradient Cooling Fuel Feed Systems
Fission Product Drive	Wire Wheels	Thin Wires Radiation and FP Resistant Magnetic Field Interaction

has a high melting point and very good thermal conductivity to allow transpiration cooling. The nozzle must also withstand hydrogen embrittlement and fission product attack. The same material may be necessary as a first wall liner in several concepts.

As mentioned before, the other common aspect is fuel storage and handling. Many of the concepts require a continuous feed system of highly corrosive (or interactive) fuel. The materials which can be used as feed lines, storage vessels, or recovery lines must be able to withstand attack by multi-phase uranium, fluorine, or both.

In the more advanced concepts, the compatibility and interactions of the materials with strong magnetic fields may become important. Generation, stability, and lifetime of the critical fields may be significantly impacted by surrounding materials.

In summary, the Innovative Concepts subpanel has identified several operational conditions which require advances in materials. The combination of radiation, thermal environment, fluid flows, and magnetic environment will put extremely stringent demand on material behavior. Substantial levels of support will be required to develop materials for nozzles, chamber walls, and fuel feed systems if these concepts are to be realized.

References

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X. SUMMARY

The Panel on Fuels, Materials and Related Technologies has produced a useful initial plan for the development of fuels and materials for SEI applications. The plans need to be enhanced once better, detailed designs of concepts become available. However, there is sufficient information available to start the development process as work on concept designs are initiated. In this section the major points of the reports are reviewed.

For fuels development, the most cost effective approach was to exploit the fundamental commonality of the solid core fuel forms for early development work. Thus, NERVA type fuel (composite and solid solution), particle bed type fuel and cermet fuel development should be initiated first, since these form the building blocks of essentially all of the candidate concept fuel forms for NTP. The initial work would consist primarily of the development of fabrication technology, evaluation of lifetime behavior under hot hydrogen flow conditions (non-nuclear tests), and fission product retention behavior under irradiation conditions. These would serve as screening tests. The most promising candidate fuels would be taken through the series on non-nuclear and in-reactor tests required to establish their design and safety characteristics, prior to integral ground testing the system. For NEP the pin fuel development work in progress in SP-100 and the thermionics programs will form the initial data base; this will be supplemented by cermet fuel, and NDR and PBR fuel for advanced LMR and GCR's respectively.

For materials development, the lack of definition by concept developers required that a broad range of materials be considered for orderly development at this stage. It was felt by the Panel members that materials development was as critical an issue for nuclear propulsion as fuels development and that this fact appeared to be not considered in the early planning by the decision makers. For the various classes of materials a set of development steps were proposed covering fabrication, property determination, compatibility assessments and irradiation behavior characterization.

A brief analysis of other reactor technologies was included in the report for completeness. It is recommended that these areas be developed further in the near term and the plans implemented in a balanced reactor development program.

Since requirements for fabrication and test facilities for the development of fuels and materials form an important output of the panel's work, a summary of the requirements is presented separately in this section. The summary requirements are extracted from the more detailed assessments presented in Sections VI and VII. Tables X.1, X.2 and X.3 present the summary information

This information has been forwarded to the Facilities Panel for their evaluation of the adequacy of existing facilities. In general, there are a number of facilities where the screening and early work can be done, although there could be scheduling problems with other programs. The major issues are the costs associated with the capsule and loop tests in existing reactors as well as the very major cost of the nuclear furnace.

For the sake of completeness, the availability of Soviet reactor test facilities needs to be mentioned. The offer has been made to several U.S. visitors to the Soviet Union (including this Panel chairman in November 1991) as well as by Soviet managers during their visits to the U.S. There are several test reactors in which fuels and materials irradiations might be performed. A particularly interesting possibility is the use of the test facility in Semipolitinsk for full power fuel element and assembly testing. Clearly these possibilities need detailed considerations since there are political and long-term economic considerations beyond the technical and near-term financial ones. The state of these facilities needs to be evaluated and long-term international collaborative plans need to be considered before such decisions can be made.

Table X.1 Recommended Facilities Requirements for NTP Fuels & Core Materials

FACILITY REQUIREMENTS	MISSION GOALS/OBJECTIVES
Fuel Fabrication and Assembly Category I SNM Facility capable of processing 200 kg U and 1000 fuel elements per year: feedstock preparation; powder preparation; sphere fabrication; sintering, CVD coating; extrusion; hot pressing; graphitizing; brazing; electron beam, laser, and GTA welding; assembly lines; inspections;quality assurance; scrap recovery; and waste treatment.	• Recapture fabrication procedures • Determine phase equilibrium and melting points • Develop new fuels and fuel forms • Develop new fabrication procedures • Fabricate test fuels and fuel elements • Develop fuel element joining techniques • Pilot plant fabrication of test cores • Develop spent fuel recovery procedures • Demonstrate quality-assured procedures
Ex-Pile Testing and Characterization Lab Adjunct to the Fuel Fabrication facility: analytical chemistry, ceramography, NDE, mechanical testing, high temperature testing, H2 testing, compatiblity testing, and kinetic, physical, and thermodynamic properties.	**Quantitatively understand:** • Thermal transport of material • Thermal stability of fuels and coatings • Chemical stability of fuels and coatings • Thermal stress resistance • Thermal properties for design • Component compatibility • Mass-loss and degradation caused by H2 reactions. • Thermal transient response
Hot Gas Testing Lab Capable of heating NTP fuel elements to 3500 K in flowing hydrogen, with data collection and analysis, post-test characterization, hydrogen and SNM containment	**Quantitatively understand:** • Corrosion mechanisms • Hydrogen compatibility at high gas flow rates • Coating integrity and stability at high gas flow rates • Fuel and coating mass loss at high gas flow rates
Capsule/Test Reactor Small test reactor with instrumented capsules, fuel temperatures to 3500 K for 10 hours, in hydrogen atmospheres, NDE equipment, data collection and analysis, in-line fission gas analysis	• Screening of solid solution fuel forms **Quantitatively understand:** • Fission product release • Hydrogen compatibility • Irradiation induced swelling • Compatibility with fission products
Transient Test Reactor Rapid thermal transient testing of fuel elements and assemblies	• Restart and cycling capability • Thermal stress resistance • Off-normal operation • Fission product release
Nuclear Furnace Able to duplicate operating conditions of a full scale NTP reactor with data collection and analysis, fission product containment, and prototype gas flow rate	• Restart and cycling capability • Element/element interactions • Corrosion mechanics • Statistical irradiation data
Hot Cells Burnup analysis, neutron radiography, profilometry, gamma scan, ceramograpy, fission gas analysis, SEM, microprobe, analytical chemistry.	• Postirradiation examination of tests for fission gas release, swelling, mass loss, compatibility, etc.

Table X.2 Recommended Nuclear Electric Propulsion Reactor Facilities Requirements

FACILITY REQUIREMENTS	MISSION GOALS/OBJECTIVES
Fuel Fabrication and Assembly	
Category 1 SNM Facility Capable of Processing 200 kg U and 1000 fuel elements per year: Feedstock Preparation, Powder Preparation, Pressing, Sintering, HIPing, Bonding Brazing, Welding, Annealing, Assembly Lines	• Develop Low Swelling, Stable UN & UO2 • Develop Long-Life Cladding • Develop Automated Fabrication Procedures • Fabricate Test Fuels and Fuel Elements • Demonstrate Quality Assured Procedures • Pilot Plant Fabrication of Test Cores
Ex-Pile Testing and Characterization	**Quantitatively Understand:**
Adjunct to the Fuel Fabrication Facility: Analytical Chemistry, Ceramography, NDE, Mechanical Testing, High Temperature Testing, Vibration Testing, Compatibility Testing, Kinetic and Thermodynamic Properties	• Thermal Stability of Fuels & Cladding • Fuel/Cladding/Coolant Compatibility • Fuel/Cladding/Fission Product Interactions • Fuel Pin Launch Vibration Tests
Lithium Loop Facility	**Quantitatively Understand:**
Capable of Heating NEP Fuel Pins to 1600 K in Flowing Lithium, with Data Collection and Analysis, Post Test Characterization	• Breached Pin Behavior • Material Transport • Fuel/Cladding/Lithium Compatibility
Instrumented Irradiation Test Loop	**Quantitatively Understand:**
Small Test Reactor with Instrumented Capsules in Flowing Lithium Loops, Fuel Temperatures to 2000 K, Burnup to 10 at.%, with NDE Equipment, Data Collection & Analysis	• Fuel Swelling & Fission Gas Release • Lithium (and other liquid metals) Compatibility • Fission Product Interactions • Cladding Creep • Screening of New Fuel Forms
Transient Test Reactor	
Rapid Thermal Transient Testing of Fuel Pins and Assemblies	• Thermal Stress Resistance • Off Normal Operation • Fission Product Release
Integrated Ground Assembly Test	
Able to Duplicate Operating Conditions of a of Full Scale NEP Reactor	• Element/Element Interactions • Statistical Irradiation Data • Full Core Demonstration
Hot Cells	
Burnup Analysis, Neutron Radiography, Profilometry, Gamma Scan, Ceramography, Fission Gas Analysis, SEM, Microprobe, Analytical Chemistry	• Postirradiation Examination of Tests for Fission Gas Release, Swelling, Mass Loss, Compatibility, etc

Table X.3 Recommended Facilities Requirements for Materials

FACILITY REQUIREMENTS	MISSION GOALS/OBJECTIVES
<u>Fabrication/Processing</u> • Facilities with past experience to develop and qualify fabrication processes for: - Refractory alloys - Ceramic matrix composite - Metal matrix - Carbon composite	• Recapture fabrication methods • Develop new methods • Fabricate samples for initial screening and feasibility tests • Fabricate components as needed • Demonstrate QA procedures
<u>Mechanical Properties Testing Labs</u> • Capabilities to test ultra-high vacuum, high temperature creep - High temperature tensile strength - Pressurized tube creep - High temperature mechanical properties of ceramics	<u>Quantitatively determine</u> • Required mechanical properties • Pre- and post-irradiation • Compile properties data base • Develop safety margins
<u>Compatibility Test Facilities</u> • Alkali metal test facilities (Li, NaK) - Static and flowing systems - Ability to test for thousands of hours of continuous operation at high vacuum conditions - Proven experience and safety record - Extensive diagnostics on site • Hydrogen compatibility test facilities • Atomic oxygen test laboratory • High temperature tribological laboratory	
<u>Radiation Test Facilities</u> • Capsule/loop testing • Transient reactor • Nuclear Furnace	<u>Quantitatively determine</u> • Radiation
<u>Hot Cells</u> Radiography, profilometry, metallography, ceramography, SEM, mechanical properties test	• Post irradiation examination of materials samples -- to gauge radiation damage

APPENDICES

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APPENDIX A
PANEL MEMBERSHIP

Members

S. Bhattacharyya	ANL	Chairman
R. Titran	NASA/LeRC	Vice Chairman
S. Howe	LANL	Vice Chairman
B. Matthews	LANL	
C. Olsen	INEL	
R. Cooper	ORNL	
F. Wyant	SNL	
S. Wright	SNL	
C. Walter	LLNL	
F. Panisko	PNL	
D. Schweitzer	BNL	
F. Jankowski	AF Phillips Lab.	
A. Whittaker	NASA/MSFC	
W. Stark	LANL	

Industry and Other Observers*

R. Brengle	Rocketdyne
J. Kerr/D. Husser	Babcock & Wilcox
J. Holloway	Pratt and Whitney
C. Sastre	BNL
S. Bailey	GE
G. Hoffman	DOE/ORO
I. Helms	NUS

* There were several other attendees at some meetings. In addition, there were several requests for minutes from other industrial people.

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APPENDIX B
MEETING DATES AND LOCATION

1. **Panel Meetings**

Date	Location
1/10/91	Albuquerque
2/06/91	Washington, DC
3/14/91	Los Alamos
5/08/91	Hanford
6/12/91	Idaho Falls
8/14/91	Argonne, IL

2. **Steering Committee Meetings**

Date	Location
4/23-24/91	Cleveland

3. **Panel Chairman Meetings**

Date	Location
2/05/91	Washington, D. C.
6/10/91	Idaho Falls

4. **Crosscut Panel Meetings**

Date	Location
6/11/91	Idaho Falls
1/92	Albuquerque

5. In addition, there have been significant activities undertaken in subgroups.

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APPENDIX C

TARGET MILESTONES FOR NUCLEAR THERMAL PROPULSION

Date	Milestone
1991	Facility requirements/approach defined
1992	Lab-scale demonstration of 2700K reactor fuel
1994	Complete conceptual designs of selected concepts for piloted Mars mission
1995	Nuclear furnace facility complete
1996	Select NTR system for systems testing
1997	Flight system design freeze
1999	Systems facility construction complete
2001	First NTR reactor test complete
2006	Full system ground testing complete verifying Technology Readiness Level (TLR) 6 for NTR

The following milestones are included to insure focus towards and operational system.

2011	First lunar robotic flight of NTR system
2013	First human-piloted lunar flight of NTR system
2014	First Mars robotic flight of NTR system
2016	First human-piloted Mars NTR exploration mission

APPENDIX C (cont.)

TARGET MILESTONES FOR NUCLEAR ELECTRIC PROPULSION

Date	Milestone
1991	Establish NEP requirements for concept systems study
1993	Complete 500 kW electric propulsion testing facility and designs for high power (MW class) electric thrusters
1994	Complete candidate systems study for reactor power source, conversion, power processing, and control concepts
1997	Complete breadboard demo of megawatt class electric thruster technology
2000	Verify 1000 hours of life for 500 kW electric propulsion system (MPD and ion options)
2005	Complete a ground tests to verify megawatt class power/propulsion system
2006	Verify Technology Readiness Level (TRL) 6 through flight test of 500 kW subscale NEP vehicle

The following milestones are included here to insure focus towards an operational system.

2010	First flight of lunar cargo vehicle
2014	First flight of Mars cargo vehicle
2016	First flight of Mars piloted vehicle

APPENDIX D
ISSUE SCORING AND RANKING FOR NEP AND NTP CONCEPTS

In order to provide recommendations with regard to the facilities that will be required for the development of NEP and NTP reactors, we wrote down a number of issues that apply to particular or generic concepts. These issues were grouped into five main categories:

Performance

Fabrication

Ex-reactor tests

In-reactor tests

Facilities

Although our motivation was to assess the commonality of the facilities required among the concepts, a considerable amount of other significant data was obtained in the process.

A varying number of issues were listed for each main category. We then requested all the concept focal points to provide their assessment of the importance of these issues by scoring the appropriate issues from 5 to 1 (most to least important). Respondents could add issues as desired but were asked to work to a total of 200 points. Several scored over 200 and we used our judgment to scale their scoring down to 200. In the case of the SP-100-like concept (E1) the submitted score was 72. This scoring was maintained without change in our basic tabulation, but we dropped it from subsequent data manipulations.

A fairly good response was obtained: Nine responses each were received for NEP and NTP concepts from a possible 11 and 15, respectively. Table D-1 provides a list of all the concepts proposed at the 1991 summer workshops. The list includes a designator for each concept.

The first character of the alpha-numeric designator is E or T depending on whether the concept is for NEP or NTP respectively. In the case of the NEP concepts, the sequential numbers following E are assigned in the same order as the concepts are presented in John Barnett's workshop feedback presentation (Ref. D-1). His ordering

was grouped by fuel material. We also followed fuel groupings to order the NTP concepts (presented by John Clark in Ref. D-2) and assigned sequential numbers to those concepts accordingly. These designators are used to identify the concepts in Tables D-2 through D-11.

An index to these tables is provided below:

Table D-1 **Concept Designations, proposing organization, and concept focal points.**

Designator	Organization	Focal Point
NEP		
E1 — SP100 Scaleup	GE	P. Pluta
E2 — 10 MWe Rankine	LLNL	C. Walter
E3 — Potassium Rankine	Rocketdyne	J. Mills
E4 — RMBLR	PNL	B. Johnson
E5 — ENABLER	Westinghouse	B. Pierce
E6 — NEPTUNE	Ohio State University	P. Turchi
E7 — Particle Bed	BNL	J. Powell
E8 — Pellet Bed	University of New Mexico	M. El-Genk
E9 — In-core Thermionic	GA	T. Van Hagan
E10 — TORCHLITE	PNL	B. Reid
E11 — Vapor Core	University of Florida	N. Diaz

NTP

T1 — ENABLER	Westinghouse	B. Pierce
T2 — Low Pressure Core	INEL	J. Ramsthaler
T3 — DUMBO	LANL	W. Kirk
T4 — Particle Bed	BNL	H. Ludewig
T5 — Pellet Bed	University of New Mexico	M. El-Genk
T6 — NIMF	Martin Marietta	R. Zubrin
T7 — Hybrid	PNL	B. Reid
T8 — Wire Core	Rocketdyne	R. Harty
T9 — Cermet	GE	G. Kruger
T10 — Foil	SNL	S. Wright
T11 — LARS	BNL	H. Ludewig
T12 — Droplet Core	University of Florida	N. Diaz
T13 — Gas Core	Sverdrup	R. Ragsdale
T14 — Vapor Core	University of Florida	N. Diaz
T15 — Light Bulb	United Technologies Research Center	T. Latham

References

D-1 Barnett, J. W., NEP Technologies: Overview of the NASA/DOE/DOD NEP Workshop, Proceedings 8th Symposium on Space Nuclear Power Systems, American Institute of Physics CONF 910116, Part 2, p. 511, January 1991.

D-2 Clark, J. S., A Comparison of NTP Concepts: Results of a Workshop, Proceedings 8th Symposium on Space Nuclear Power Systems, American Institute of Physics CONF 910116, Part 2, p. 740, January 1991.

Table D-2 Basic Tabulation - All Proposed Concepts

(shaded) No data received

CONCEPTS

Category	Nitride				Carbide				Oxide		UF	Carbide							N	Oxide		LIQ		Vapor			
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	Total
• **Performance Issues**																											
- Mid Band Corrosion/Cracking											1	4	1	1					1						1		9
- H2 Compatibility								5				4	4	5	5	5			3	3	2				5		41
- Coating Integrity & Stability	3				1		4	4	2			4	1	2	4	4				4	5				5		43
- Thermal Stress Resistance		1			2			3	4		1	4	3	5		3			1	4	3				2		36
- Fission Product Release	3	3	4	5			5	2	5				3	1	5	2			1	5	2						46
- Component Compatibility		3						3	2		1		1			3				1	5				1		20
- Element/Element Interactions		5			3		3					3	1	2	3				2	4	2				1		29
- High Temperature Vaporization		1					2				2		3	5	3				2						2		20
- Melting Point							2	2			1		3	5	3	2			4						1		23
- Composition Stability		3	1		3		3	3	3		1	3	3	1	4	3			2	5	3				1		42
- Irradiation Induced Phenomena	3	5	1	5	5		4	3	5		5	3	1		1	3			2		2						48
- UN Swelling to 10 at % Burnup		1		5																							6
- UN Fission Gas Release to 10 at % Burnup	5	1		5																							11
- Cladding/UN/Fission Product Interactions		5	3	5															2								15
- UN/Cladding Compatibility for 10 years		1		5																							6
- Transient & Off-Normal Performance	3	3	3	5	2		2	3	2		1	2	3	3	4	3			2	5	3				1		50
- Fuel Pin Integrity During Launch				5					3				1						1		5						15
- UO2 Swelling at 2400K									5											4							9
- Emitter Creep Distortion									5																		5
- Fission Product Interactions		3	3				4	3	3		1		1			3			2	4					1		28
- UO2/Tungsten Compatibility for 10 years									5																		5
- Insulator Performance for 10 years									5		2																7
- Burnup			5	5	2		3												1								16
- Fission Product Migration			3	5			3	3	2		1		1		2	3			1	4					1		29
- Component Mech & Chem Compatibility		3	2	5	1		4	3	3		1	1	1	4	4	3				4	3				1		43
- Cycling Capability				5	1		2	2			1	1	3	1	4	2			1	4	4				1		32
- Power/Cooling Matching				5	2		3	2			2	2	3	5	3	2			1	1	4				1		36
- Fuel Element Integrity		3		5	3		4	2				3	4	5	5	2			3		2				2		43
- Neutronics & Control	5	5	3		1		4	2			4	1	4	5	4	2			2	2	5				3		52
- Turbine Bearings in Inert Atmosphere, CO2								4								4					3						11
- High-Temperature Thermometry	5	3	1		1		3	4			3	1	1	5	3	4			3	3	4				3		47
- Start-Up Neutron Detector	3	1	1	5	1		3	3			1	1	1		3	3			2	3					1		32
- Hyperconducting Generators				5				2								2											9
- Superconducting Generators					2			2								2											6
- High-Temperature Heat Pipes		5		5	4																						14
- Radiation Shielding		5	3		1		3	3	5		1	2		2	3	3			2	3					1		37
- Moderator					1		3		3		3	1	2	3	2						5				5		28
- Liquid Metal Compatibility		3	3	5							5																16
- Rad-Hard High-Temp Electronics	5	3	3	5	3		3	5			2	3			3	5			1	2	3				2		48
- Shielding Materials		5	1	5	1		3	2	3		1	1	1	2	3	2			1	2					1		34

Table D-2 Basic Tabulation - All Proposed Concepts (cont.)

▒ No data received

CONCEPTS

Category	Nitride				Carbide				Oxide		UF	Carbide							N	Oxide		LIQ		Vapor			
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	Total
• **Performance Issues (cont.)**																											
- Rad-Hard Thermometry	3	1			1		3	5			1	1	1	2	3	5			2						1		29
- Lithium Thaw	3	1	3								2																9
- Light-Weight, High-Temp Heat Pipes	3		5	5	4		3	3			4					3									1		31
- Thermoelectric Pump Materials		3	5	5																							13
- Refractory Metal Technology for Turbo-Mach		5	5		2			2				2				2											18
- Fuel Element Fabricability					3							3		4													10
- Insulator Performance in H2 >3000K														5													5
- Fuel Constituent Mass Loss vs. Time & Temp					3							3		5													11
- Fuel Dimension/Geometry Design Opt.					2							2		4													8
- Potassium Turbine			4																								4
- Cermet Fuel Thermal Testing			5																								5
- Nozzle Specific Impulse												2	3														5
- Alternate Nozzle Designs												1	1														2
- High Temp Pref. Carbides					2							5	1														8
- Hydrogen Atom Recombination													2														2
- MHD Channel/Electrodes					3						5																8
- Carbide Fuels							5								5												10
TOTAL	44	81	67	110	60	0	81	80	65	0	53	63	58	82	79	80	0	0	45	67	65	0	0	0	45	0	1225

Table D-2 Basic Tabulation - All Proposed Concepts (cont.)

No data received

CONCEPTS

	Nitride				Carbide				Oxide		UF	Carbide							N	Oxide		LIQ		Vapor			
Category	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	Total
• **Fabrication Issues**																											
- Recapture Rover/NERVA Technology				5	5			4			1	4	1	5		4				3					1		33
- Sphere Fabrication					1		4	5				1	2		4	5				3							25
- High CTE Graphite					4		3	5				4			3	5									2		26
- Extrusion & Firing or Hot Pressing					3			3				3	3	5		3				3					3		26
- Coating Technologies	3		3				4	5	2			2	2	2	4	5				4	5				5		46
- Joining Refractory Metals		5	2		1			2	5		5	1	2			2			3	5					2		35
- QA & QC			3	5			3		5		3		3	5	3				3		5				5		43
- Phase Distribution					2		3					2	2		3				2								14
- Homogeneous, Solid Solution					2							2	2	3					2								11
- Forming & Sintering		3							2		3		3						4		4				4		23
- Characterization		3			2				3		3	2	2						2						3		20
- Pilot Plant Capability					2						1	3							4	5					1		16
- Demonstrate Bonding Plant Capability											1								1	4	4				1		11
- Develop Sealed Rhenium or W-25Re Clad		5									1								5	5							16
- UN Stoichiometry		3																	3								6
- Develop High-Temp, Low Swelling Fuel			2	5					5										3								15
- Develop W/HfC Fabrication									4		5		1												4		14
- Automate Process				5							1		1						5	1					1		14
- Qualify Integrated Fabrication Process				5					3		2		1	5					4	5					2		27
- Sphere Fabrication Optimization							3	3					2		3	3											14
- Hot & Cold Frit Development							5	3					4		5	3											20
- Carbothermic Reduction & Sintering													3												2		5
- Reactor Control Algorithm	3	5	1								1		2						1		5				1		19
- Moderator Design & Process Development											1		1	2					1		5				1		11
- High-Curie Temp Magnetic Materials (NEP)			4																								4
- Hyper-Conducting Materials Develop (NEP)				5							2																7
- Low-Weight, High-Temp Radiators	5		5	5	4		3	2			5														1		30
- Thermocouple Alloy Development					1		2	3				1	1	5	1	5			1	3	3						26
- Design Flexibility			2								1		1	5					1						1		11
- Neutron Detector Material Development		1	1		1			3			1	1				3			2	3					1		17
- Recapture Cermet Fuel Technology			5	5															2	5							17
- Develop New Process																					5						5
- High-Temperature Emitters									5																		5
- Seals			4						4		3		1								3				3		18
- Sheath Insulators									4					3							3						10
- Integral Resevoirs									4																		4
- Refractory Metal Forms & Coatings		3	5					3	2		5		2			3			3	2					5		33
- Carbon-Carbon Composites, Refractory			5		1		3	3				3	1	2	3	3					5				5		34
- Sel/Demo of W25Re Cermet Fab Process			5																								5

Table D-2 Basic Tabulation - All Proposed Concepts (cont.)

No data received

CONCEPTS

	Nitride				Carbide				Oxide		UF	Carbide							N	Oxide		LIQ		Vapor			
Category	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	Total
• **Fabrication Issues (cont.)**																											
- Particle Bed Algorithm													1														1
- Carbide Fuels					5		4					5	2		5												21
- Fiber Reinforced Carbide Fuel													1														1
																											739
TOTAL	11	28	47	40	34	0	37	44	48	0	45	34	47	42	34	44	0	0	52	51	47	0	0	0	54	0	739

Table D-2 Basic Tabulation - All Proposed Concepts (cont.)

(shaded) No data received

CONCEPTS

Category	Nitride				Carbide				Oxide		UF	Carbide							N	Oxide		LIQ		Vapor			
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	Total
• **Ex-Reactor Tests**																											
- Property Measurement		5	5		4		3	5	2		4	5	4	2	3	5			2	5	5				3		62
- Characterization		3	2		2		5		2		2	3	3	3					2	4	4						35
- Thermal Stress Testing			2		2		3	4	3		4	3	2	5	3	4			2	4	3				2		46
- Hot Hydrogen Testing								4				4	4	5	4	4			4	4	3				4		40
- Element Interaction Tests		3			3		3		3		1	3	1	3	3				2	3					5		33
- Measure UN/Fission Product Interactions		3	1																1						1		6
- Verify UN Stoichiometry Control		5	1																1								7
- Breached Pin Lithium Loop Test		4																									4
- Effect of Chemical Interactions on Cladding		3							2		1								3								9
- Launch Vibration Tests	5		1	5	5		2	4			1	3	2		4	4			1	3	3				5		48
- UO2/Emitter/Fission Product Interactions									5																1		6
- UO2 Stability at 2400 K				5					4											5							14
- Measure Insulator Properties									4		3			5													12
- Transient Testing		3	3	5	3			3			3	4	4	4		3			2	4	2						43
- Component Mech & Chem Interaction Tests					3		2		4		4	4	2		2				5	4	2				3		35
- Moderator Stability Tests							3				1		2		3						5				4		18
- Bearing Wear & Stability	3	3	5		5		2						1								3				1		23
- Cyclic Testing				5	3		3				2	1	3		3				2		4				1		27
- Heat Pipe Performance Testing	3		5	5	4		3		3		5														2		30
- Liquid Metal Testing		3	5								3														1		12
- H2 and Liquid Metal Testing											1														1		2
- Cermet Compression/Distortion Testing			5																						1		6
- Nozzle Tests												2	2														4
- H + H — H2 Recombination													2														2
- MHD Channel Performance											4				5												9
																											533
TOTAL	11	35	35	25	34	0	29	20	32	0	39	32	32	27	30	20	0	0	27	36	34	0	0	0	35	0	533

Table D-2 Basic Tabulation - All Proposed Concepts (cont.)

[shaded box] No data received

CONCEPTS

Category	Nitride				Carbide				Oxide		UF	Carbide							N	Oxide		LIQ		Vapor			
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	Total
• **In-Reactor Tests**																											
- Instrumented Fuel Element Tests		3			5		3	3	5			5	4	2	3	3			5		5				4		50
- Single Element Tests				5	4		2	3	2		1	4	3	2	3	3					4				2		38
- Statistical Tests		1			3		3		3		1	3	4		3				2						3		26
- Transient & Off-Normal Tests		3	2	5	3		3	3	3		2	3	1		3	3			3						2		39
- Prototypical Assembly Tests		3			1		4		3		1	1	4		3				5		3				1		29
- Electrical Output Instrumented Tests									3																2		5
- Fuel Pellet Irradiation		3						4					1			4			5	5							22
- Safety Tests (To Failure)		5	3	5	4		3	4			1	4	4		3	4			3		3				3		49
- Particle Irradiations							4	5					1		2	5											17
- Shielding Materials Performance		1	1		2		2	3			1	2	2		2	3			2	3	4				1		29
- Neutron Detector Performance	3	1	2		1		2	3			2	1	2		2	3			2	3					2		29
- Thermometry Performance & Calibration		1	2		1		3				2	1	1		3				1		2				2		19
- Electron, Neutron, & Gamma Irradiation		3	1		3						3	3	1						1						3		18
- Heat Pipe Testing	3	3	2	5	4						2														1		20
- Cermet Fuel Irradiation			5																								5
- Hydrogen Atom Recombination									3																		3
- H2 Excitation by Fission Products									4												5						9
- Fuel chemistry/composition stability					4						5	4													4		17
- Reactor Control/Feedback Mechanism					1						5	1													5		12
																											436
TOTAL	6	27	18	20	36	0	29	28	26	0	26	32	28	4	27	28	0	0	29	11	26	0	0	0	35	0	436

Table D-2 Basic Tabulation - All Proposed Concepts (cont.)

▒ No data received

Category	CONCEPTS																										
	Nitride				Carbide				Oxide		UF	Carbide							N	Oxide		LIQ			Vapor		
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	Total
• **Facilities**																											
- Fuel Fabrication & Assembly (Cermet)		3	5	5				4	4				3	5		4			4	5	5						47
- Ex-Pile Testing & Characterization Lab		1	2		2			4	3		1	2	1	5		4			4	5	3				2		39
- Hot Gas Testing Lab					1			3			2	2	2	5		3			3	5	3				4		33
- Single Element Test Reactor					2		3				1		3		3				5						3		20
- Transient Reactor			2		4				2		2	3	2		3				5		3				2		28
- Nuclear Furnace					2		3				1	5	2	5					5		5				2		30
- Hot Cells			1		3				3		2	3	4	5	3				3	2	3				2		34
- Lithium Loop		5	5				3				5																18
- Integrated Ground Assembly Test					5			4	3		5	3	4	5	3	4			5	5					5		51
- Liquid Metal Testing Laboratory		3	5				2				3																13
- Gamma & Neutron Irradiation		3			2		3				4	2	1		2				3						2		22
- Materials Fabrication		3	5		4		3	4	3		2	4	3	5	3	4			2	5	3				3		56
- Tribology Laboratory							2								3												5
- Instrumented Irrad Test Loop for One FE		5					3		4				2						4								18
- Properties & Characterization Laboratory		3	3		3		2	5	4		1	3	1		3	5			1	4					1		39
- Irradiation Capsules		3			1				3			1	1		3				1	4							17
- Hot Hydrogen Testing Laboratory								4				2	3	5	4	4			2		3				5		32
- Fuel Post-Hot-Gas-Test Measurements Lab					2							2															4
- Potassium Boiling/Condensing Laboratory			5								3			5													13
- Critical Assembly					2							2	1														5
- Cold Flow												2	1														3
- Nozzle Facility												3	1														4
- Nuclear-MHD Generator Facility					3						5																8
																											539
TOTAL	0	29	33	5	36	0	24	28	29	0	37	39	35	45	30	28	0	0	47	35	28	0	0	0	31	0	539
																											3472
GRAND TOTAL	72	200	200	200	200	0	200	200	200	0	200	200	200	200	200	200	0	0	200	200	200	0	0	0	200	0	3472

Table D-3 NEP, NTP Concepts - Global Issue Ranking

CONCEPTS

	Nitride			Carbide			O	UF	Carbide					N	Oxide		V		Main
Category	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- Property Measurement	5	5		4	3	5	2	4	5	4	2	3	5	2	5	5	3	62	Ex-R
- Materials Fabrication	3	5		4	3	4	3	2	4	3	5	3	4	2	5	3	3	56	Fac
- Integrated Ground Assembly Test				5		4	3	5	3	4	5	3	4	5	5		5	51	Fac
- Instrumented Fuel Element Tests	3			5	3	3	5		5	4	2	3	3	5		5	4	50	In-R
- Safety Tests (To Failure)	5	3	5	4	3	4		1	4	4		3	4	3		3	3	49	In-R
- Transient & Off-Normal Performance	3	3	5	2	2	3	2	1	2	3	3	4	3	2	5	3	1	47	Per
- Neutronics & Control	5	3		1	4	2		4	1	4	5	4	2	2	2	5	3	47	Per
- Fuel Fabrication & Assembly (Cermet)	3	5	5			4	4			3	5		4	4	5	5		47	Fac
- Thermal Stress Testing		2		2	3	4	3	4	3	2	5	3	4	2	4	3	2	46	Ex-R
- Irradiation Induced Phenomena	5	1	5	5	4	3	5	5	3	1		1	3	2		2		45	Per
- Fission Product Release	3	4	5		5	2	5			3	1	5	2	1	5	2		43	Per
- Component Mech & Chem Compatibility	3	2	5	1	4	3	3	1	1	1	4	4	3		4	3	1	43	Per
- Fuel Element Integrity	3		5	3	4	2			3	4	5	5	2	3		2	2	43	Per
- Rad-Hard High-Temp Electronics	3	3	5	3	3	5		2	3			3	5	1	2	3	2	43	Per
- Coating Technologies		3			4	5	2		2	2	2	4	5		4	5	5	43	Fab
- QA & QC		3	5		3		5	3		3	5	3		3		5	5	43	Fab
- Transient Testing	3	3	5	3		3		3	4	4	4		3	2	4	2		43	Ex-R
- Launch Vibration Tests		1	5	5	2	4		1	3	2		4	4	1	3	3	5	43	Ex-R
- Composition Stability	3	1		3	3	3	3	1	3	3	1	4	3	2	5	3	1	42	Per
- High-Temperature Thermometry	3	1		1	3	4		3	1	1	5	3	4	3	3	4	3	42	Per
- H2 Compatibility						5			4	4	5	5	5	3	3	2	5	41	Per
- Coating Integrity & Stability				1	4	4	2		4	1	2	4	4		4	5	5	40	Per
- Hot Hydrogen Testing						4			4	4	5	4	4	4	4	3	4	40	Ex-R
- Transient & Off-Normal Tests	3	2	5	3	3	3	3	2	3	1		3	3	3			2	39	In-R
- Ex-Pile Testing & Characterization Lab	1	2		2		4	3	1	2	1	5		4	4	5	3	2	39	Fac
- Properties & Characterization Laboratory	3	3		3	2	5	4	1	3	1		3	5	1	4		1	39	Fac
- Single Element Tests			5	4	2	3	2	1	4	3	2	3	3			4	2	38	In-R
- Radiation Shielding	5	3		1	3	3	5	1	2		2	3	3	2	3		1	37	Per
- Thermal Stress Resistance	1			2		3	4	1	4	3	5		3	1	4	3	2	36	Per
- Power/Cooling Matching			5	2	3	2		2	2	3	5	3	2	1	1	4	1	36	Per
- Joining Refractory Metals	5	2		1		2	5	5	1	2			2	3	5		2	35	Fab
- Component Mech & Chem Interaction Tests				3	2		4	4	4	2		2		5	4	2	3	35	Ex-R
- Characterization	3	2		2	5		2	2	3	3	3			2	4	4		35	Ex-R
- Shielding Materials	5	1	5	1	3	2	3	1	1	1	2	3	2	1	2		1	34	Per
- Carbon-Carbon Composites, Refractory		5		1	3	3			3	1	2	3	3			5	5	34	Fab
- Hot Cells		1		3			3	2	3	4	5	3		3	2	3	2	34	Fac
- Recapture Rover/NERVA Technology			5	5		4		1	4	1	5		4		3		1	33	Fab
- Refractory Metal Forms & Coatings	3	5				3	2	5		2			3	3	2		5	33	Fab
- Element Interaction Tests	3			3	3		3	1	3	1	3	3		2	3		5	33	Ex-R
- Hot Gas Testing Lab				1		3		2	2	2	5		3	3	5	3	4	33	Fac
- Cycling Capability			5	1	2	2		1	1	3	1	4	2	1	4	4	1	32	Per

Table D-3 NEP, NTP Concepts - Global Issue Ranking (cont.)

CONCEPTS

Category	Nitride			Carbide			O	UF	Carbide					N	Oxide		V		Main
	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- Hot Hydrogen Testing Laboratory						4			2	3	5	4	4	2		3	5	32	Fac
- Nuclear Furnace				2	3			1	5	2	5			5		5	2	30	Fac
- Element/Element Interactions	5			3	3				3	1	2	3		2	4	2	1	29	Per
- Fission Product Migration		3	5		3	3	2	1		1		2	3	1	4		1	29	Per
- Start-Up Neutron Detector	1	1	5	1	3	3		1	1	1		3	3	2	3		1	29	Per
- Prototypical Assembly Tests	3			1	4		3	1	1	4		3		5		3	1	29	In-R
- Shielding Materials Performance	1	1		2	2	3		1	2	2		2	3	2	3	4	1	29	In-R
- Fission Product Interactions	3	3			4	3	3	1		1			3	2	4		1	28	Per
- Moderator				1	3		3	3	1	2	3	2				5	5	28	Per
- Light-Weight, High-Temp Heat Pipes		5	5	4	3	3		4					3				1	28	Per
- Transient Reactor		2		4			2	2	3	2		3		5		3	2	28	Fac
- Qualify Integrated Fabrication Process			5				3	2		1	5			4	5		2	27	Fab
- Cyclic Testing			5	3	3			2	1	3		3		2		4	1	27	Ex-R
- Heat Pipe Performance Testing		5	5	4	3		3	5									2	27	Ex-R
- Rad-Hard Themometry	1			1	3	5		1	1	1	2	3	5	2			1	26	Per
- High CTE Graphite				4	3	5			4			3	5				2	26	Fab
- Extrusion & Firing or Hot Pressing				3		3			3	3	5		3		3		3	26	Fab
- Thermocouple Alloy Development				1	2	3			1	1	5	1	5	1	3	3		26	Fab
- Statistical Tests	1			3	3		3	1	3	4		3		2			3	26	In-R
- Neutron Detector Performance	1	2		1	2	3		2	1	2		2	3	2	3		2	26	In-R
- Sphere Fabrication				1	4	5			1	2		4	5		3			25	Fab
- Low-Weight, High-Temp Radiators		5	5	4	3	2		5									1	25	Fab
- Melting Point					2	2		1		3	5	3	2	4			1	23	Per
- Forming & Sintering	3						2	3		3				4		4	4	23	Fab
- Fuel Pellet Irradiation	3					4				1			4	5	5			22	In-R
- Gamma & Neutron Irradiation	3			2	3			4	2	1		2		3			2	22	Fac
- Carbide Fuels				5	4				5	2		5						21	Fab
- Component Compatibility	3					3	2	1		1			3		1	5	1	20	Per
- High Temperature Vaporization	1				2			2		3	5	3		2			2	20	Per
- Characterization	3			2			3	3	2	2				2			3	20	Fab
- Hot & Cold Frit Development					5	3				4		5	3					20	Fab
- Bearing Wear & Stability	3	5		5	2					1						3	1	20	Ex-R
- Single Element Test Reactor				2	3			1		3		3		5			3	20	Fac
- Thermometry Performance & Calibration	1	2		1	3			2	1	1		3		1		2	2	19	In-R
- Refractory Metal Technology for Turbo-Mach	5	5		2		2			2				2					18	Per
- Seals		4					4	3		1						3	3	18	Fab
- Moderator Stability Tests					3			1		2		3				5	4	18	Ex-R
- Electron, Neutron, & Gamma Irradiation	3	1		3				3	3	1				1			3	18	In-R
- Lithium Loop	5	5			3			5										18	Fac
- Instrumented Irrad Test Loop for One FE	5				3		4			2				4				18	Fac
- Neutron Detector Material Development	1	1		1		3		1	1				3	2	3		1	17	Fab

Table D-3 NEP, NTP Concepts - Global Issue Ranking (cont.)

CONCEPTS

	Nitride			Carbide			O	UF	Carbide					N	Oxide		V		Main
Category	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- Recapture Cermet Fuel Technology		5	5											2	5			17	Fab
- Particle Irradiations					4	5				1		2	5					17	In-R
- Heat Pipe Testing	3	2	5	4				2									1	17	In-R
- Fuel chemistry/composition stability				4				5	4								4	17	In-R
- Irradiation Capsules	3			1			3		1	1		3		1	4			17	Fac
- Burnup		5	5	2	3									1				16	Per
- Liquid Metal Compatibility	3	3	5					5										16	Per
- Pilot Plant Capability				2				1	3					4	5		1	16	Fab
- Develop Sealed Rhenium or W-25Re Clad	5							1						5	5			16	Fab
- Reactor Control Algorithm	5	1						1		2				1		5	1	16	Fab
- Cladding/UN/Fission Product Interactions	5	3	5											2				15	Per
- Fuel Pin Integrity During Launch			5				3			1				1		5		15	Per
- Develop High-Temp, Low Swelling Fuel		2	5				5							3				15	Fab
- High-Temperature Heat Pipes	5		5	4														14	Per
- Phase Distribution				2	3				2	2		3		2				14	Fab
- Develop W/HfC Fabrication							4	5		1							4	14	Fab
- Automate Process			5					1		1				5	1		1	14	Fab
- Sphere Fabrication Optimization					3	3				2		3	3					14	Fab
- UO2 Stability at 2400 K			5				4								5			14	Ex-R
- Thermoelectric Pump Materials	3	5	5															13	Per
- Liquid Metal Testing Laboratory	3	5			2			3										13	Fac
- Potassium Boiling/Condensing Laboratory		5						3			5							13	Fac
- Measure Insulator Properties							4	3			5							12	Ex-R
- Liquid Metal Testing	3	5						3									1	12	Ex-R
- Reactor Control/Feedback Mechanism				1				5	1								5	12	In-R
- Turbine Bearings in Inert Atmosphere, CO2						4							4			3		11	Per
- Fuel Constituent Mass Loss vs. Time & Temp				3					3		5							11	Per
- Homogeneous, Solid Solution				2					2	2	3			2				11	Fab
- Demonstrate Bonding Plant Capability								1						1	4	4	1	11	Fab
- Moderator Design & Process Development								1		1	2			1		5	1	11	Fab
- Design Flexibility		2						1		1	5			1			1	11	Fab
- Fuel Element Fabricability				3					3		4							10	Per
- Carbide Fuels					5							5						10	Per
- Sheath Insulators							4				3					3		10	Fab
- Mid Band Corrosion/Cracking								1	4	1	1			1			1	9	Per
- UO2 Swelling at 2400K							5								4			9	Per
- Hyperconducting Generators			5			2							2					9	Per
- Effect of Chemical Interactions on Cladding	3						2	1						3				9	Ex-R
- MHD Channel Performance								4				5						9	Ex-R
- H2 Excitation by Fission Products							4									5		9	In-R
- Fuel Dimension/Geometry Design Opt.				2					2		4							8	Per

Table D-3 NEP, NTP Concepts - Global Issue Ranking (cont.)

CONCEPTS

Category	Nitride			Carbide			O	UF	Carbide					N	Oxide		V		Main
	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- High Temp Pref. Carbides				2					5	1								8	Per
- MHD Channel/Electrodes				3				5										8	Per
- Nuclear-MHD Generator Facility				3				5										8	Fac
- Insulator Performance for 10 years							5	2										7	Per
- Hyper-Conducting Materials Develop (NEP)			5					2										7	Fab
- Verify UN Stoichiometry Control	5	1												1				7	Ex-R
- UN Swelling to 10 at % Burnup	1		5															6	Per
- UN Fission Gas Release to 10 at % Burnup	1		5															6	Per
- UN/Cladding Compatibility for 10 years	1		5															6	Per
- Superconducting Generators				2		2							2					6	Per
- Lithium Thaw	1	3						2										6	Per
- UN Stoichiometry	3													3				6	Fab
- UO2/Emitter/Fission Product Interactions							5										1	6	Ex-R
- Cermet Compression/Distortion Testing		5															1	6	Ex-R
- Measure UN/Fission Product Interactions	3	1												1			1	6	Ex-R
- Emitter Creep Distortion							5											5	Per
- UO2/Tungsten Compatibility for 10 years							5											5	Per
- Insulator Performance in H2 >3000K											5							5	Per
- Cermet Fuel Thermal Testing		5																5	Per
- Nozzle Specific Impulse									2	3								5	Per
- Carbothermic Reduction & Sintering										3							2	5	Fab
- Develop New Process																5		5	Fab
- High-Temperature Emitters							5											5	Fab
- Sel/Demo of W25Re Cermet Fab Process		5																5	Fab
- Electrical Output Instrumented Tests							3										2	5	In-R
- Cermet Fuel Irradiation		5																5	In-R
- Tribology Laboratory					2							3						5	Fac
- Critical Assembly				2					2	1								5	Fac
- Potassium Turbine		4																4	Per
- High-Curie Temp Magnetic Materials (NEP)		4																4	Fab
- Integral Resevoirs							4											4	Fab
- Nozzle Tests									2	2								4	Ex-R
- Fuel Post-Hot-Gas-Test Measurements Lab				2					2									4	Fac
- Nozzle Facility									3	1								4	Fac
- Breached Pin Lithium Loop Test	4																	4	Ex-R
- Hydrogen Atom Recombination							3											3	In-R
- Cold Flow									2	1								3	Fac
- Alternate Nozzle Designs									1	1								2	Per
- Hydrogen Atom Recombination										2								2	Per
- H2 and Liquid Metal Testing								1									1	2	Ex-R
- H + H — H2 Recombination										2								2	Ex-R

Table D-3 NEP, NTP Concepts - Global Issue Ranking (cont.)

CONCEPTS

Category	Nitride			Carbide			O	UF	Carbide					N	Oxide		V		Main
	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- Particle Bed Algorithm										1								1	Fab
- Fiber Reinforced Carbide Fuel										1								1	Fab

Table D-4 NEP Concepts - Global Issue Ranking

	CONCEPTS									
	Nitride			Carbide			O	UF		Main
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total	Issue
- Irradiation Induced Phenomena	5	1	5	5	4	3	5	5	33	Per
- Property Measurement	5	5		4	3	5	2	4	28	Ex-R
- Safety Tests (To Failure)	5	3	5	4	3	4		1	25	In-R
- Heat Pipe Performance Testing		5	5	4	3		3	5	25	Ex-R
- Materials Fabrication	3	5		4	3	4	3	2	24	Fac
- Fission Product Release	3	4	5		5	2	5		24	Per
- Rad-Hard High-Temp Electronics	3	3	5	3	3	5		2	24	Per
- Transient & Off-Normal Tests	3	2	5	3	3	3	3	2	24	In-R
- Light-Weight, High-Temp Heat Pipes		5	5	4	3	3		4	24	Per
- Low-Weight, High-Temp Radiators		5	5	4	3	2		5	24	Fab
- Component Mech & Chem Compatibility	3	2	5	1	4	3	3	1	22	Per
- Transient & Off-Normal Performance	3	3	5	2	2	3	2	1	21	Per
- Fuel Fabrication & Assembly (Cermet)	3	5	5			4	4		21	Fac
- Properties & Characterization Laboratory	3	3		3	2	5	4	1	21	Fac
- Radiation Shielding	5	3		1	3	3	5	1	21	Per
- Shielding Materials	5	1	5	1	3	2	3	1	21	Per
- Transient Testing	3	3	5	3		3		3	20	Ex-R
- Joining Refractory Metals	5	2		1		2	5	5	20	Fab
- Instrumented Fuel Element Tests	3			5	3	3	5		19	In-R
- Neutronics & Control	5	3		1	4	2		4	19	Per
- QA & QC		3	5		3		5	3	19	Fab
- Thermal Stress Testing		2		2	3	4	3	4	18	Ex-R
- Launch Vibration Tests		1	5	5	2	4		1	18	Ex-R
- Refractory Metal Forms & Coatings	3	5				3	2	5	18	Fab
- Lithium Loop	5	5			3			5	18	Fac
- Integrated Ground Assembly Test				5		4	3	5	17	Fac
- Fuel Element Integrity	3		5	3	4	2			17	Per
- Composition Stability	3	1		3	3	3	3	1	17	Per
- Single Element Tests			5	4	2	3	2	1	17	In-R
- Fission Product Migration		3	5		3	3	2	1	17	Per
- Fission Product Interactions	3	3			4	3	3	1	17	Per
- Characterization	3	2		2	5		2	2	16	Ex-R
- Heat Pipe Testing	3	2	5	4				2	16	In-R
- Liquid Metal Compatibility	3	3	5					5	16	Per
- High-Temperature Thermometry	3	1		1	3	4		3	15	Per
- Recapture Rover/NERVA Technology			5	5		4		1	15	Fab
- Start-Up Neutron Detector	1	1	5	1	3	3		1	15	Per
- Bearing Wear & Stability	3	5		5	2				15	Ex-R

Table D-4 NEP Concepts - Global Issue Ranking (cont.)

Category	CONCEPTS: Nitride			Carbide			O	UF		Main
	E2	E3	E4	E5	E7	E8	E9	E11	Total	Issue
- Burnup		5	5	2	3				15	Per
- Coating Technologies		3			4	5	2		14	Fab
- Power/Cooling Matching			5	2	3	2		2	14	Per
- Refractory Metal Technology for Turbo-Mach	5	5		2		2			14	Per
- High-Temperature Heat Pipes	5		5	4					14	Per
- Ex-Pile Testing & Characterization Lab	1	2		2		4	3	1	13	Fac
- Component Mech & Chem Interaction Tests				3	2		4	4	13	Ex-R
- Element Interaction Tests	3			3	3		3	1	13	Ex-R
- Cyclic Testing			5	3	3			2	13	Ex-R
- Cladding/UN/Fission Product Interactions	5	3	5						13	Per
- Thermoelectric Pump Materials	3	5	5						13	Per
- Liquid Metal Testing Laboratory	3	5			2			3	13	Fac
- Carbon-Carbon Composites, Refractory		5		1	3	3			12	Fab
- Prototypical Assembly Tests	3			1	4		3	1	12	In-R
- High CTE Graphite				4	3	5			12	Fab
- Gamma & Neutron Irradiation	3			2	3			4	12	Fac
- Instrumented Irrad Test Loop for One FE	5				3		4		12	Fac
- Develop High-Temp, Low Swelling Fuel		2	5				5		12	Fab
- Coating Integrity & Stability				1	4	4	2		11	Per
- Thermal Stress Resistance	1			2		3	4	1	11	Per
- Cycling Capability			5	1	2	2		1	11	Per
- Element/Element Interactions	5			3	3				11	Per
- Rad-Hard Themometry	1			1	3	5		1	11	Per
- Statistical Tests	1			3	3		3	1	11	In-R
- Neutron Detector Performance	1	2		1	2	3		2	11	In-R
- Characterization	3			2			3	3	11	Fab
- Seals		4					4	3	11	Fab
- Liquid Metal Testing	3	5						3	11	Ex-R
- Shielding Materials Performance	1	1		2	2	3		1	10	In-R
- Moderator				1	3		3	3	10	Per
- Transient Reactor		2		4			2	2	10	Fac
- Qualify Integrated Fabrication Process			5				3	2	10	Fab
- Sphere Fabrication				1	4	5			10	Fab
- Electron, Neutron, & Gamma Irradiation	3	1		3				3	10	In-R
- Recapture Cermet Fuel Technology		5	5						10	Fab
- Hot Cells		1		3			3	2	9	Fac
- Carbide Fuels				5	4				9	Fab
- Component Compatibility	3					3	2	1	9	Per

Table D-4 NEP Concepts - Global Issue Ranking (cont.)

	CONCEPTS									
	Nitride			Carbide			O	UF		Main
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total	Issue
- Thermometry Performance & Calibration	1	2		1	3			2	9	In-R
- Particle Irradiations					4	5			9	In-R
- Fuel chemistry/composition stability				4				5	9	In-R
- Develop W/HfC Fabrication							4	5	9	Fab
- UO2 Stability at 2400 K			5				4		9	Ex-R
- Forming & Sintering	3						2	3	8	Fab
- Hot & Cold Frit Development					5	3			8	Fab
- Fuel Pin Integrity During Launch			5				3		8	Per
- Potessium Boiling/Condensing Laboratory		5						3	8	Fac
- MHD Channel/Electrodes				3				5	8	Per
- Nuclear-MHD Generator Facility				3				5	8	Fac
- Fuel Pellet Irradiation	3					4			7	In-R
- Neutron Detector Material Development	1	1		1		3		1	7	Fab
- Irradiation Capsules	3			1			3		7	Fac
- Reactor Control Algorithm	5	1						1	7	Fab
- Measure Insulator Properties							4	3	7	Ex-R
- Hyperconducting Generators			5			2			7	Per
- Insulator Performance for 10 years							5	2	7	Per
- Hyper-Conducting Materials Develop (NEP)			5					2	7	Fab
- Hot Gas Testing Lab				1		3		2	6	Fac
- Nuclear Furnace				2	3			1	6	Fac
- Extrusion & Firing or Hot Pressing				3		3			6	Fab
- Thermocouple Alloy Development				1	2	3			6	Fab
- Single Element Test Reactor				2	3			1	6	Fac
- Develop Sealed Rhenium or W-25Re Clad	5							1	6	Fab
- Automate Process			5					1	6	Fab
- Sphere Fabrication Optimization					3	3			6	Fab
- Reactor Control/Feedback Mechanism				1				5	6	In-R
- Effect of Chemical Interactions on Cladding	3						2	1	6	Ex-R
- Verify UN Stoichiometry Control	5	1							6	Ex-R
- UN Swelling to 10 at % Burnup	1		5						6	Per
- UN Fission Gas Release to 10 at % Burnup	1		5						6	Per
- UN/Cladding Compatibility for 10 years	1		5						6	Per
- Lithium Thaw	1	3						2	6	Per
- H2 Compatibility						5			5	Per
- Melting Point					2	2		1	5	Per
- High Temperature Vaporization	1				2			2	5	Per
- Phase Distribution				2	3				5	Fab

Table D-4 NEP Concepts - Global Issue Ranking (cont.)

CONCEPTS

Category	Nitride			Carbide			O	UF		Main
	E2	E3	E4	E5	E7	E8	E9	E11	Total	Issue
- Carbide Fuels					5				5	Per
- UO2 Swelling at 2400K							5		5	Per
- UO2/Emitter/Fission Product Interactions							5		5	Ex-R
- Cermet Compression/Distortion Testing		5							5	Ex-R
- Emitter Creep Distortion							5		5	Per
- UO2/Tungsten Compatibility for 10 years							5		5	Per
- Cermet Fuel Thermal Testing		5							5	Per
- High-Temperature Emitters							5		5	Fab
- Sel/Demo of W25Re Cermet Fab Process		5							5	Fab
- Cermet Fuel Irradiation		5							5	In-R
- Hot Hydrogen Testing						4			4	Ex-R
- Hot Hydrogen Testing Laboratory						4			4	Fac
- Moderator Stability Tests					3			1	4	Ex-R
- Turbine Bearings in Inert Atmosphere, CO2						4			4	Per
- Sheath Insulators							4		4	Fab
- MHD Channel Performance								4	4	Ex-R
- H2 Excitation by Fission Products							4		4	In-R
- Superconducting Generators				2		2			4	Per
- Measure UN/Fission Product Interactions	3	1							4	Ex-R
- Potassium Turbine		4							4	Per
- High-Curie Temp Magnetic Materials (NEP)		4							4	Fab
- Integral Resevoirs							4		4	Fab
- Breached Pin Lithium Loop Test	4								4	Ex-R
- Pilot Plant Capability				2				1	3	Fab
- Fuel Constituent Mass Loss vs. Time & Temp				3					3	Per
- Design Flexibility		2						1	3	Fab
- Fuel Element Fabricability				3					3	Per
- UN Stoichiometry	3								3	Fab
- Electrical Output Instrumented Tests							3		3	In-R
- Hydrogen Atom Recombination							3		3	In-R
- Homogeneous, Solid Solution				2					2	Fab
- Fuel Dimension/Geometry Design Opt.				2					2	Per
- High Temp Pref. Carbides				2					2	Per
- Tribology Laboratory					2				2	Fac
- Critical Assembly				2					2	Fac
- Fuel Post-Hot-Gas-Test Measurements Lab				2					2	Fac
- Demonstrate Bonding Plant Capability								1	1	Fab
- Moderator Design & Process Development								1	1	Fab

Table D-4 NEP Concepts - Global Issue Ranking (cont.)

	CONCEPTS									
	Nitride			Carbide			O	UF		Main
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total	Issue
- Mid Band Corrosion/Cracking								1	1	Per
- H2 and Liquid Metal Testing								1	1	Ex-R
- Insulator Performance in H2 >3000K									0	Per
- Nozzle Specific Impulse									0	Per
- Carbothermic Reduction & Sintering									0	Fab
- Develop New Process									0	Fab
- Nozzle Tests									0	Ex-R
- Nozzle Facility									0	Fac
- Cold Flow									0	Fac
- Alternate Nozzle Designs									0	Per
- Hydrogen Atom Recombination									0	Per
- H + H — H2 Recombination									0	Ex-R
- Particle Bed Algorithm									0	Fab
- Fiber Reinforced Carbide Fuel									0	Fab

Table D-5 NTP Concepts - Global Issue Ranking

CONCEPTS

Category	Carbide					N	Oxide		V		Main
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- H2 Compatibility	4	4	5	5	5	3	3	2	5	36	Per
- Hot Hydrogen Testing	4	4	5	4	4	4	4	3	4	36	Ex-R
- Property Measurement	5	4	2	3	5	2	5	5	3	34	Ex-R
- Integrated Ground Assembly Test	3	4	5	3	4	5	5		5	34	Fac
- Materials Fabrication	4	3	5	3	4	2	5	3	3	32	Fac
- Instrumented Fuel Element Tests	5	4	2	3	3	5		5	4	31	In-R
- Coating Technologies	2	2	2	4	5		4	5	5	29	Fab
- Coating Integrity & Stability	4	1	2	4	4		4	5	5	29	Per
- Neutronics & Control	1	4	5	4	2	2	2	5	3	28	Per
- Thermal Stress Testing	3	2	5	3	4	2	4	3	2	28	Ex-R
- Hot Hydrogen Testing Laboratory	2	3	5	4	4	2		3	5	28	Fac
- High-Temperature Thermometry	1	1	5	3	4	3	3	4	3	27	Per
- Hot Gas Testing Lab	2	2	5		3	3	5	3	4	27	Fac
- Transient & Off-Normal Performance	2	3	3	4	3	2	5	3	1	26	Per
- Fuel Fabrication & Assembly (Cermet)		3	5		4	4	5	5		26	Fac
- Fuel Element Integrity	3	4	5	5	2	3		2	2	26	Per
- Ex-Pile Testing & Characterization Lab	2	1	5		4	4	5	3	2	26	Fac
- Launch Vibration Tests	3	2		4	4	1	3	3	5	25	Ex-R
- Composition Stability	3	3	1	4	3	2	5	3	1	25	Per
- Thermal Stress Resistance	4	3	5		3	1	4	3	2	25	Per
- Hot Cells	3	4	5	3		3	2	3	2	25	Fac
- Safety Tests (To Failure)	4	4		3	4	3		3	3	24	In-R
- QA & QC		3	5	3		3		5	5	24	Fab
- Nuclear Furnace	5	2	5			5		5	2	24	Fac
- Transient Testing	4	4	4		3	2	4	2		23	Ex-R
- Power/Cooling Matching	2	3	5	3	2	1	1	4	1	22	Per
- Component Mech & Chem Interaction Tests	4	2		2		5	4	2	3	22	Ex-R
- Carbon-Carbon Composites, Refractory	3	1	2	3	3			5	5	22	Fab
- Component Mech & Chem Compatibility	1	1	4	4	3		4	3	1	21	Per
- Single Element Tests	4	3	2	3	3			4	2	21	In-R
- Cycling Capability	1	3	1	4	2	1	4	4	1	21	Per
- Element Interaction Tests	3	1	3	3		2	3		5	20	Ex-R
- Extrusion & Firing or Hot Pressing	3	3	5		3		3		3	20	Fab
- Thermocouple Alloy Development	1	1	5	1	5	1	3	3		20	Fab
- Fission Product Release		3	1	5	2	1	5	2		19	Per
- Rad-Hard High-Temp Electronics	3			3	5	1	2	3	2	19	Per
- Characterization	3	3	3			2	4	4		19	Ex-R
- Shielding Materials Performance	2	2		2	3	2	3	4	1	19	In-R

Table D-5 NTP Concepts - Global Issue Ranking (cont.)

CONCEPTS

Category	Carbide					N	Oxide		V		Main
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- Properties & Characterization Laboratory	3	1		3	5	1	4		1	18	Fac
- Recapture Rover/NERVA Technology	4	1	5		4		3		1	18	Fab
- Element/Element Interactions	3	1	2	3		2	4	2	1	18	Per
- Moderator	1	2	3	2				5	5	18	Per
- Transient Reactor	3	2		3		5		3	2	18	Fac
- Melting Point		3	5	3	2	4			1	18	Per
- Prototypical Assembly Tests	1	4		3		5		3	1	17	In-R
- Qualify Integrated Fabrication Process		1	5			4	5		2	17	Fab
- Radiation Shielding	2		2	3	3	2	3		1	16	Per
- Transient & Off-Normal Tests	3	1		3	3	3			2	15	In-R
- Joining Refractory Metals	1	2			2	3	5		2	15	Fab
- Refractory Metal Forms & Coatings		2			3	3	2		5	15	Fab
- Rad-Hard Themometry	1	1	2	3	5	2			1	15	Per
- Statistical Tests	3	4		3		2			3	15	In-R
- Neutron Detector Performance	1	2		2	3	2	3		2	15	In-R
- Sphere Fabrication	1	2		4	5		3			15	Fab
- Forming & Sintering		3				4		4	4	15	Fab
- Fuel Pellet Irradiation		1			4	5	5			15	In-R
- High Temperature Vaporization		3	5	3		2			2	15	Per
- Start-Up Neutron Detector	1	1		3	3	2	3		1	14	Per
- Cyclic Testing	1	3		3		2		4	1	14	Ex-R
- High CTE Graphite	4			3	5				2	14	Fab
- Single Element Test Reactor		3		3		5			3	14	Fac
- Moderator Stability Tests		2		3				5	4	14	Ex-R
- Shielding Materials	1	1	2	3	2	1	2		1	13	Per
- Pilot Plant Capability	3					4	5		1	13	Fab
- Irradiation Induced Phenomena	3	1		1	3	2		2		12	Per
- Fission Product Migration		1		2	3	1	4		1	12	Per
- Carbide Fuels	5	2		5						12	Fab
- Hot & Cold Frit Development		4		5	3					12	Fab
- Fission Product Interactions		1			3	2	4		1	11	Per
- Component Compatibility		1			3		1	5	1	11	Per
- Gamma & Neutron Irradiation	2	1		2		3			2	10	Fac
- Thermometry Performance & Calibration	1	1		3		1		2	2	10	In-R
- Neutron Detector Material Development	1				3	2	3		1	10	Fab
- Irradiation Capsules	1	1		3		1	4			10	Fac
- Develop Sealed Rhenium or W-25Re Clad						5	5			10	Fab
- Demonstrate Bonding Plant Capability						1	4	4	1	10	Fab

Table D-5 NTP Concepts - Global Issue Ranking (cont.)

	CONCEPTS										
	Carbide					N	Oxide		V		Main
Category	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- Moderator Design & Process Development		1	2			1		5	1	10	Fab
- Characterization	2	2				2			3	9	Fab
- Reactor Control Algorithm		2				1		5	1	9	Fab
- Phase Distribution	2	2		3		2				9	Fab
- Homogeneous, Solid Solution	2	2	3			2				9	Fab
- Electron, Neutron, & Gamma Irradiation	3	1				1			3	8	In-R
- Particle Irradiations		1		2	5					8	In-R
- Fuel chemistry/composition stability	4								4	8	In-R
- Automate Process		1				5	1		1	8	Fab
- Sphere Fabrication Optimization		2		3	3					8	Fab
- Fuel Constituent Mass Loss vs. Time & Temp	3		5							8	Per
- Design Flexibility		1	5			1			1	8	Fab
- Mid Band Corrosion/Cracking	4	1	1			1			1	8	Per
- Seals		1						3	3	7	Fab
- Recapture Cermet Fuel Technology						2	5			7	Fab
- Fuel Pin Integrity During Launch		1				1		5		7	Per
- Turbine Bearings in Inert Atmosphere, CO2					4			3		7	Per
- Fuel Element Fabricability	3		4							7	Per
- Instrumented Irrad Test Loop for One FE		2				4				6	Fac
- Reactor Control/Feedback Mechanism	1								5	6	In-R
- Sheath Insulators			3					3		6	Fab
- Fuel Dimension/Geometry Design Opt.	2		4							6	Per
- High Temp Pref. Carbides	5	1								6	Per
- Bearing Wear & Stability		1						3	1	5	Ex-R
- Develop W/HfC Fabrication		1							4	5	Fab
- UO2 Stability at 2400 K							5			5	Ex-R
- Potessium Boiling/Condensing Laboratory			5							5	Fac
- Measure Insulator Properties			5							5	Ex-R
- Carbide Fuels				5						5	Per
- MHD Channel Performance				5						5	Ex-R
- H2 Excitation by Fission Products								5		5	In-R
- Insulator Performance in H2 >3000K			5							5	Per
- Nozzle Specific Impulse	2	3								5	Per
- Carbothermic Reduction & Sintering		3							2	5	Fab
- Develop New Process								5		5	Fab
- Light-Weight, High-Temp Heat Pipes					3				1	4	Per
- Refractory Metal Technology for Turbo-Mach	2				2					4	Per
- UO2 Swelling at 2400K							4			4	Per

Table D-5 NTP Concepts - Global Issue Ranking (cont.)

CONCEPTS

Category	Carbide					N	Oxide		V		Main
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- Nozzle Tests	2	2								4	Ex-R
- Nozzle Facility	3	1								4	Fac
- Develop High-Temp, Low Swelling Fuel						3				3	Fab
- Effect of Chemical Interactions on Cladding						3				3	Ex-R
- UN Stoichiometry						3				3	Fab
- Tribology Laboratory				3						3	Fac
- Critical Assembly	2	1								3	Fac
- Cold Flow	2	1								3	Fac
- Heat Pipe Performance Testing									2	2	Ex-R
- Cladding/UN/Fission Product Interactions						2				2	Per
- Hyperconducting Generators					2					2	Per
- Superconducting Generators					2					2	Per
- Measure UN/Fission Product Interactions						1			1	2	Ex-R
- Electrical Output Instrumented Tests									2	2	In-R
- Fuel Post-Hot-Gas-Test Measurements Lab	2									2	Fac
- Alternate Nozzle Designs	1	1								2	Per
- Hydrogen Atom Recombination		2								2	Per
- H + H — H2 Recombination		2								2	Ex-R
- Low-Weight, High-Temp Radiators									1	1	Fab
- Heat Pipe Testing									1	1	In-R
- Burnup						1				1	Per
- Liquid Metal Testing									1	1	Ex-R
- Verify UN Stoichiometry Control						1				1	Ex-R
- UO2/Emitter/Fission Product Interactions									1	1	Ex-R
- Cermet Compression/Distortion Testing									1	1	Ex-R
- H2 and Liquid Metal Testing									1	1	Ex-R
- Particle Bed Algorithm		1								1	Fab
- Fiber Reinforced Carbide Fuel		1								1	Fab
- Lithium Loop										0	Fac
- Liquid Metal Compatibility										0	Per
- High-Temperature Heat Pipes										0	Per
- Thermoelectric Pump Materials										0	Per
- Liquid Metal Testing Laboratory										0	Fac
- MHD Channel/Electrodes										0	Per
- Nuclear-MHD Generator Facility										0	Fac
- Insulator Performance for 10 years										0	Per
- Hyper-Conducting Materials Develop (NEP)										0	Fab
- UN Swelling to 10 at % Burnup										0	Per

Table D-5 NTP Concepts - Global Issue Ranking (cont.)

	CONCEPTS										
	Carbide					N	Oxide		V		Main
Category	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total	Issue
- UN Fission Gas Release to 10 at % Burnup										0	Per
- UN/Cladding Compatibility for 10 years										0	Per
- Lithium Thaw										0	Per
- Emitter Creep Distortion										0	Per
- UO2/Tungsten Compatibility for 10 years										0	Per
- Cermet Fuel Thermal Testing										0	Per
- High-Temperature Emitters										0	Fab
- Sel/Demo of W25Re Cermet Fab Process										0	Fab
- Cermet Fuel Irradiation										0	In-R
- Potassium Turbine										0	Per
- High-Curie Temp Magnetic Materials (NEP)										0	Fab
- Integral Resevoirs										0	Fab
- Breached Pin Lithium Loop Test										0	Ex-R
- Hydrogen Atom Recombination										0	In-R

Table D-6 NEP, NTP Concepts - Ranked by Main Issue

	CONCEPTS																	
	Nitride			Carbide			O	UF	Carbide					N	Oxide		V	
Category	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• Performance Issues																		
- Transient & Off-Normal Performance	3	3	5	2	2	3	2	1	2	3	3	4	3	2	5	3	1	47
- Neutronics & Control	5	3		1	4	2		4	1	4	5	4	2	2	2	5	3	47
- Irradiation Induced Phenomena	5	1	5	5	4	3	5	5	3	1		1	3	2		2		45
- Fission Product Release	3	4	5		5	2	5			3	1	5	2	1	5	2		43
- Component Mech & Chem Compatibility	3	2	5	1	4	3	3	1	1	1	4	4	3		4	3	1	43
- Fuel Element Integrity	3		5	3	4	2			3	4	5	5	2	3		2	2	43
- Rad-Hard High-Temp Electronics	3	3	5	3	3	5		2	3			3	5	1	2	3	2	43
- Composition Stability	3	1		3	3	3	3	1	3	3	1	4	3	2	5	3	1	42
- High-Temperature Thermometry	3	1		1	3	4		3	1	1	5	3	4	3	3	4	3	42
- H2 Compatibility						5			4	4	5	5	5	3	3	2	5	41
- Coating Integrity & Stability				1	4	4	2		4	1	2	4	4		4	5	5	40
- Radiation Shielding	5	3		1	3	3	5	1	2		2	3	3	2	3		1	37
- Thermal Stress Resistance	1			2		3	4	1	4	3	5		3	1	4	3	2	36
- Power/Cooling Matching			5	2	3	2		2	2	3	5	3	2	1	1	4	1	36
- Shielding Materials	5	1	5	1	3	2	3	1	1	1	2	3	2	1	2		1	34
- Cycling Capability			5	1	2	2		1	1	3	1	4	2	1	4	4	1	32
- Element/Element Interactions	5			3	3				3	1	2	3		2	4	2	1	29
- Fission Product Migration		3	5		3	3	2	1		1		2	3	1	4		1	29
- Start-Up Neutron Detector	1	1	5	1	3	3		1	1	1		3	3	2	3		1	29
- Fission Product Interactions	3	3			4	3	3	1		1			3	2	4		1	28
- Moderator				1	3		3	3	1	2	3	2				5	5	28
- Light-Weight, High-Temp Heat Pipes		5	5	4	3	3		4					3				1	28
- Rad-Hard Themometry	1			1	3	5		1	1	1	2	3	5	2			1	26
- Melting Point					2	2		1		3	5	3	2	4			1	23
- Component Compatibility	3					3	2	1		1			3		1	5	1	20
- High Temperature Vaporization	1				2			2		3	5	3		2			2	20
- Refractory Metal Technology for Turbo-Mach	5	5		2		2			2				2					18
- Burnup		5	5	2	3									1				16
- Liquid Metal Compatibility	3	3	5					5										16
- Cladding/UN/Fission Product Interactions	5	3	5											2				15
- Fuel Pin Integrity During Launch			5				3			1				1		5		15
- High-Temperature Heat Pipes	5		5	4														14
- Thermoelectric Pump Materials	3	5	5															13
- Turbine Bearings in Inert Atmosphere, CO2						4							4			3		11
- Fuel Constituent Mass Loss vs. Time & Temp				3					3		5							11
- Fuel Element Fabricability				3					3		4							10
- Carbide Fuels					5							5						10
- Mid Band Corrosion/Cracking								1	4	1	1			1			1	9
- UO2 Swelling at 2400K							5								4			9
- Hyperconducting Generators			5			2							2					9

Table D-6 NEP, NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

	Nitride			Carbide			O	UF	Carbide					N	Oxide		V	
Category	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **Performance Issues (cont.)**																		
- Fuel Dimension/Geometry Design Opt.				2					2		4							8
- High Temp Pref. Carbides				2					5	1								8
- MHD Channel/Electrodes				3				5										8
- Insulator Performance for 10 years							5	2										7
- UN Swelling to 10 at % Burnup	1		5															6
- UN Fission Gas Release to 10 at % Burnup	1		5															6
- UN/Cladding Compatibility for 10 years	1		5															6
- Superconducting Generators				2		2							2					6
- Lithium Thaw	1	3						2										6
- Emitter Creep Distortion							5											5
- UO2/Tungsten Compatibility for 10 years							5											5
- Insulator Performance in H2 >3000K											5							5
- Cermet Fuel Thermal Testing		5																5
- Nozzle Specific Impulse									2	3								5
- Potassium Turbine		4																4
- Alternate Nozzle Designs									1	1								2
- Hydrogen Atom Recombination										2								2

Table D-6 NEP, NTP Concepts - Ranked by Main Issue (cont.)

	CONCEPTS																	
	Nitride			Carbide			O	UF	Carbide					N	Oxide		V	
Category	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **Fabrication Issues**																		
- Coating Technologies		3			4	5	2		2	2	2	4	5		4	5	5	43
- QA & QC		3	5		3		5	3		3	5	3		3		5	5	43
- Joining Refractory Metals	5	2		1		2	5	5	1	2			2	3	5		2	35
- Carbon-Carbon Composites, Refractory		5		1	3	3			3	1	2	3	3			5	5	34
- Recapture Rover/NERVA Technology			5	5		4		1	4	1	5		4		3		1	33
- Refractory Metal Forms & Coatings	3	5				3	2	5		2			3	3	2		5	33
- Qualify Integrated Fabrication Process			5				3	2		1	5			4	5		2	27
- High CTE Graphite				4	3	5			4			3	5				2	26
- Extrusion & Firing or Hot Pressing				3		3			3	3	5		3		3		3	26
- Thermocouple Alloy Development				1	2	3			1	1	5	1	5	1	3	3		26
- Sphere Fabrication				1	4	5			1	2		4	5		3			25
- Low-Weight, High-Temp Radiators		5	5	4	3	2		5									1	25
- Forming & Sintering	3						2	3		3				4		4	4	23
- Carbide Fuels				5	4				5	2		5						21
- Characterization	3			2			3	3	2	2				2			3	20
- Hot & Cold Frit Development					5	3				4		5	3					20
- Seals		4					4	3		1						3	3	18
- Neutron Detector Material Development	1	1		1		3		1	1				3	2	3		1	17
- Recapture Cermet Fuel Technology		5	5											2	5			17
- Pilot Plant Capability				2				1	3					4	5		1	16
- Develop Sealed Rhenium or W-25Re Clad	5							1						5	5			16
- Reactor Control Algorithm	5	1						1		2				1		5	1	16
- Develop High-Temp, Low Swelling Fuel		2	5				5							3				15
- Phase Distribution				2	3				2	2		3		2				14
- Develop W/HfC Fabrication							4	5		1							4	14
- Automate Process			5					1		1				5	1		1	14
- Sphere Fabrication Optimization					3	3				2		3	3					14
- Homogeneous, Solid Solution				2					2	2	3			2				11
- Demonstrate Bonding Plant Capability								1						1	4	4	1	11
- Moderator Design & Process Development								1		1	2			1		5	1	11
- Design Flexibility		2						1		1	5			1			1	11
- Sheath Insulators							4				3					3		10
- Hyper-Conducting Materials Develop (NEP)			5					2										7
- UN Stoichiometry	3													3				6
- Carbothermic Reduction & Sintering										3							2	5
- Develop New Process																5		5
- High-Temperature Emitters							5											5
- Sel/Demo of W25Re Cermet Fab Process		5																5
- High-Curie Temp Magnetic Materials (NEP)		4																4
- Integral Resevoirs							4											4

Table D-6 NEP, NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Nitride			Carbide			O	UF	Carbide					N	Oxide		V	
	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **Fabrication Issues (cont.)**																		
- Fiber Reinforced Carbide Fuel										1								1
- Particle Bed Algorithm										1								1

Table D-6 NEP, NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Nitride			Carbide			O	UF	Carbide					N	Oxide		V	
	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• Ex-Reactor Tests																		
- Property Measurement	5	5		4	3	5	2	4	5	4	2	3	5	2	5	5	3	62
- Thermal Stress Testing		2		2	3	4	3	4	3	2	5	3	4	2	4	3	2	46
- Launch Vibration Tests		1	5	5	2	4		1	3	2		4	4	1	3	3	5	43
- Transient Testing	3	3	5	3		3		3	4	4	4		3	2	4	2		43
- Hot Hydrogen Testing						4			4	4	5	4	4	4	4	3	4	40
- Characterization	3	2		2	5		2	2	3	3	3			2	4	4		35
- Component Mech & Chem Interaction Tests				3	2		4	4	4	2		2		5	4	2	3	35
- Element Interaction Tests	3			3	3		3	1	3	1	3	3		2	3		5	33
- Cyclic Testing			5	3	3			2	1	3		3		2		4	1	27
- Heat Pipe Performance Testing		5	5	4	3		3	5									2	27
- Bearing Wear & Stability	3	5		5	2					1						3	1	20
- Moderator Stability Tests					3			1		2		3				5	4	18
- UO2 Stability at 2400 K			5				4								5			14
- Measure Insulator Properties							4	3			5							12
- Liquid Metal Testing	3	5						3									1	12
- Effect of Chemical Interactions on Cladding	3						2	1						3				9
- MHD Channel Performance								4				5						9
- Verify UN Stoichiometry Control	5	1												1				7
- Measure UN/Fission Product Interactions	3	1												1			1	6
- UO2/Emitter/Fission Product Interactions							5										1	6
- Cermet Compression/Distortion Testing		5															1	6
- Breached Pin Lithium Loop Test	4																	4
- Nozzle Tests									2	2								4
- H2 and Liquid Metal Testing								1									1	2
- H + H — H2 Recombination										2								2

Table D-6 NEP, NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

	Nitride			Carbide			O	UF	Carbide					N	Oxide		V	
Category	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **In-Reactor Tests**																		
- Instrumented Fuel Element Tests	3			5	3	3	5		5	4	2	3	3	5		5	4	50
- Safety Tests (To Failure)	5	3	5	4	3	4		1	4	4		3	4	3		3	3	49
- Transient & Off-Normal Tests	3	2	5	3	3	3	3	2	3	1		3	3	3			2	39
- Single Element Tests			5	4	2	3	2	1	4	3	2	3	3			4	2	38
- Prototypical Assembly Tests	3			1	4		3	1	1	4		3		5		3	1	29
- Shielding Materials Performance	1	1		2	2	3		1	2	2		2	3	2	3	4	1	29
- Statistical Tests	1			3	3		3	1	3	4		3		2			3	26
- Neutron Detector Performance	1	2		1	2	3		2	1	2		2	3	2	3		2	26
- Fuel Pellet Irradiation	3					4				1			4	5	5			22
- Thermometry Performance & Calibration	1	2		1	3			2	1	1		3		1		2	2	19
- Electron, Neutron, & Gamma Irradiation	3	1		3				3	3	1				1			3	18
- Particle Irradiations					4	5				1		2	5					17
- Heat Pipe Testing	3	2	5	4				2									1	17
- Fuel chemistry/composition stability				4				5	4								4	17
- Reactor Control/Feedback Mechanism				1				5	1								5	12
- H2 Excitation by Fission Products							4									5		9
- Electrical Output Instrumented Tests							3										2	5
- Cermet Fuel Irradiation		5																5
- Hydrogen Atom Recombination							3											3

Table D-6 NEP, NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Nitride			Carbide			O	UF	Carbide					N	Oxide		V	Total
	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	
• **Facilities**																		
- Materials Fabrication	3	5		4	3	4	3	2	4	3	5	3	4	2	5	3	3	56
- Integrated Ground Assembly Test				5		4	3	5	3	4	5	3	4	5	5		5	51
- Fuel Fabrication & Assembly (Cermet)	3	5	5			4	4			3	5		4	4	5	5		47
- Ex-Pile Testing & Characterization Lab	1	2		2		4	3	1	2	1	5		4	4	5	3	2	39
- Properties & Characterization Laboratory	3	3		3	2	5	4	1	3	1		3	5	1	4		1	39
- Hot Cells		1		3			3	2	3	4	5	3		3	2	3	2	34
- Hot Gas Testing Lab				1		3		2	2	2	5		3	3	5	3	4	33
- Hot Hydrogen Testing Laboratory						4			2	3	5	4	4	2		3	5	32
- Nuclear Furnace				2	3			1	5	2	5			5		5	2	30
- Transient Reactor		2		4			2	2	3	2		3		5		3	2	28
- Gamma & Neutron Irradiation	3			2	3			4	2	1		2		3			2	22
- Single Element Test Reactor				2	3			1		3		3		5			3	20
- Lithium Loop	5	5			3			5										18
- Instrumented Irrad Test Loop for One FE	5				3		4			2				4				18
- Irradiation Capsules	3			1			3		1	1		3		1	4			17
- Liquid Metal Testing Laboratory	3	5			2			3										13
- Potassium Boiling/Condensing Laboratory		5						3			5							13
- Nuclear-MHD Generator Facility				3				5										8
- Tribology Laboratory					2							3						5
- Critical Assembly				2					2	1								5
- Fuel Post-Hot-Gas-Test Measurements Lab				2					2									4
- Nozzle Facility									3	1								4
- Cold Flow									2	1								3

Table D-7 NEP Concepts - Ranked by Main Issue

	Concepts								
	Nitride			Carbide			O	UF	
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total
• **Performance Issues**									
- Irradiation Induced Phenomena	5	1	5	5	4	3	5	5	33
- Fission Product Release	3	4	5		5	2	5		24
- Rad-Hard High-Temp Electronics	3	3	5	3	3	5		2	24
- Light-Weight, High-Temp Heat Pipes		5	5	4	3	3		4	24
- Component Mech & Chem Compatibility	3	2	5	1	4	3	3	1	22
- Transient & Off-Normal Performance	3	3	5	2	2	3	2	1	21
- Radiation Shielding	5	3		1	3	3	5	1	21
- Shielding Materials	5	1	5	1	3	2	3	1	21
- Neutronics & Control	5	3		1	4	2		4	19
- Composition Stability	3	1		3	3	3	3	1	17
- Fission Product Interactions	3	3			4	3	3	1	17
- Fission Product Migration		3	5		3	3	2	1	17
- Fuel Element Integrity	3		5	3	4	2			17
- Liquid Metal Compatibility	3	3	5					5	16
- Burnup		5	5	2	3				15
- High-Temperature Thermometry	3	1		1	3	4		3	15
- Start-Up Neutron Detector	1	1	5	1	3	3		1	15
- Power/Cooling Matching			5	2	3	2		2	14
- High-Temperature Heat Pipes	5		5	4					14
- Refractory Metal Technology for Turbo-Mach	5	5		2		2			14
- Cladding/UN/Fission Product Interactions	5	3	5						13
- Thermoelectric Pump Materials	3	5	5						13
- Coating Integrity & Stability				1	4	4	2		11
- Thermal Stress Resistance	1			2		3	4	1	11
- Element/Element Interactions	5			3	3				11
- Cycling Capability			5	1	2	2		1	11
- Rad-Hard Themometry	1			1	3	5		1	11
- Moderator				1	3		3	3	10
- Component Compatibility	3					3	2	1	9
- Fuel Pin Integrity During Launch			5				3		8
- MHD Channel/Electrodes				3				5	8
- Insulator Performance for 10 years							5	2	7
- Hyperconducting Generators			5			2			7
- UN Swelling to 10 at % Burnup	1		5						6
- UN Fission Gas Release to 10 at % Burnup	1		5						6
- UN/Cladding Compatibility for 10 years	1		5						6
- Lithium Thaw	1	3						2	6

Table D-7 NEP Concepts - Ranked by Main Issue (cont.)

	Concepts								
	Nitride			Carbide			O	UF	
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total
• **Performance Issues (cont.)**									
- H2 Compatibility						5			5
- High Temperature Vaporization	1				2			2	5
- Melting Point					2	2		1	5
- UO2 Swelling at 2400K							5		5
- Emitter Creep Distortion							5		5
- UO2/Tungsten Compatibility for 10 years							5		5
- Cermet Fuel Thermal Testing		5							5
- Carbide Fuels					5				5
- Turbine Bearings in Inert Atmosphere, CO2						4			4
- Superconducting Generators				2		2			4
- Potassium Turbine		4							4
- Fuel Element Fabricability				3					3
- Fuel Constituent Mass Loss vs. Time & Temp				3					3
- Fuel Dimension/Geometry Design Opt.				2					2
- High Temp Pref. Carbides				2					2
- Mid Band Corrosion/Cracking								1	1
- Insulator Performance in H2 >3000K									0
- Nozzle Specific Impulse									0
- Alternate Nozzle Designs									0
- Hydrogen Atom Recombination									0
									597
TOTAL	81	67	110	60	81	80	65	53	597

Table D-7 NEP Concepts - Ranked by Main Issue (cont.)

	Concepts								
	Nitride			Carbide			O	UF	
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total
• Fabrication Issues									
- Low-Weight, High-Temp Radiators		5	5	4	3	2		5	24
- Joining Refractory Metals	5	2		1		2	5	5	20
- QA & QC		3	5		3		5	3	19
- Refractory Metal Forms & Coatings	3	5				3	2	5	18
- Recapture Rover/NERVA Technology			5	5		4		1	15
- Coating Technologies		3			4	5	2		14
- High CTE Graphite				4	3	5			12
- Develop High-Temp, Low Swelling Fuel		2	5				5		12
- Carbon-Carbon Composites, Refractory		5		1	3	3			12
- Characterization	3			2			3	3	11
- Seals		4					4	3	11
- Sphere Fabrication				1	4	5			10
- Qualify Integrated Fabrication Process			5				3	2	10
- Recapture Cermet Fuel Technology		5	5						10
- Develop W/HfC Fabrication							4	5	9
- Carbide Fuels				5	4				9
- Forming & Sintering	3						2	3	8
- Hot & Cold Frit Development					5	3			8
- Reactor Control Algorithm	5	1						1	7
- Hyper-Conducting Materials Develop (NEP)			5					2	7
- Neutron Detector Material Development	1	1		1		3		1	7
- Extrusion & Firing or Hot Pressing				3		3			6
- Develop Sealed Rhenium or W-25Re Clad	5							1	6
- Automate Process			5					1	6
- Sphere Fabrication Optimization					3	3			6
- Thermocouple Alloy Development				1	2	3			6
- Phase Distribution				2	3				5
- High-Temperature Emitters							5		5
- Sel/Demo of W25Re Cermet Fab Process		5							5
- High-Curie Temp Magnetic Materials (NEP)		4							4
- Sheath Insulators							4		4
- Integral Resevoirs							4		4
- Pilot Plant Capability				2				1	3
- UN Stoichiometry	3								3
- Design Flexibility		2						1	3
- Homogeneous, Solid Solution				2					2

Table D-7 NEP Concepts - Ranked by Main Issue (cont.)

	Concepts								
	Nitride			Carbide			O	UF	
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total
• **Fabrication Issues (cont.)**									
- Demonstrate Bonding Plant Capability								1	1
- Moderator Design & Process Development								1	1
- Carbothermic Reduction & Sintering									0
- Develop New Process									0
- Particle Bed Algorithm									0
- Fiber Reinforced Carbide Fuel									0
									323
TOTAL	28	47	40	34	37	44	48	45	323

Table D-7 NEP Concepts - Ranked by Main Issue (cont.)

	Concepts								
	Nitride			Carbide			O	UF	
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total
• **Ex-Reactor Tests**									
- Property Measurement	5	5		4	3	5	2	4	28
- Heat Pipe Performance Testing		5	5	4	3		3	5	25
- Transient Testing	3	3	5	3		3		3	20
- Thermal Stress Testing		2		2	3	4	3	4	18
- Launch Vibration Tests		1	5	5	2	4		1	18
- Characterization	3	2		2	5		2	2	16
- Bearing Wear & Stability	3	5		5	2				15
- Element Interaction Tests	3			3	3		3	1	13
- Component Mech & Chem Interaction Tests				3	2		4	4	13
- Cyclic Testing			5	3	3			2	13
- Liquid Metal Testing	3	5						3	11
- UO2 Stability at 2400 K			5				4		9
- Measure Insulator Properties							4	3	7
- Verify UN Stoichiometry Control	5	1							6
- Effect of Chemical Interactions on Cladding	3						2	1	6
- UO2/Emitter/Fission Product Interactions							5		5
- Cermet Compression/Distortion Testing		5							5
- Hot Hydrogen Testing						4			4
- Measure UN/Fission Product Interactions	3	1							4
- Breached Pin Lithium Loop Test	4								4
- Moderator Stability Tests					3			1	4
- MHD Channel Performance								4	4
- H2 and Liquid Metal Testing								1	1
- Nozzle Tests									0
- H + H — H2 Recombination									0
									249
TOTAL	35	35	25	34	29	20	32	39	249

Table D-7 NEP Concepts - Ranked by Main Issue (cont.)

	Concepts								
	Nitride			Carbide			O	UF	
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total
• **In-Reactor Tests**									
- Safety Tests (To Failure)	5	3	5	4	3	4		1	25
- Transient & Off-Normal Tests	3	2	5	3	3	3	3	2	24
- Instrumented Fuel Element Tests	3			5	3	3	5		19
- Single Element Tests			5	4	2	3	2	1	17
- Heat Pipe Testing	3	2	5	4				2	16
- Prototypical Assembly Tests	3			1	4		3	1	12
- Statistical Tests	1			3	3		3	1	11
- Neutron Detector Performance	1	2		1	2	3		2	11
- Shielding Materials Performance	1	1		2	2	3		1	10
- Electron, Neutron, & Gamma Irradiation	3	1		3				3	10
- Particle Irradiations					4	5			9
- Thermometry Performance & Calibration	1	2		1	3			2	9
- Fuel chemistry/composition stability				4				5	9
- Fuel Pellet Irradiation	3					4			7
- Reactor Control/Feedback Mechanism				1				5	6
- Cermet Fuel Irradiation		5							5
- H2 Excitation by Fission Products							4		4
- Electrical Output Instrumented Tests							3		3
- Hydrogen Atom Recombination							3		3
									210
TOTAL	27	18	20	36	29	28	26	26	210

Table D-7 NEP Concepts - Ranked by Main Issue (cont.)

	Concepts								
	Nitride			Carbide			O	UF	
Category	**E2**	**E3**	**E4**	**E5**	**E7**	**E8**	**E9**	**E11**	**Total**
• **Facilities**									
- Materials Fabrication	3	5		4	3	4	3	2	24
- Fuel Fabrication & Assembly (Cermet)	3	5	5			4	4		21
- Properties & Characterization Laboratory	3	3		3	2	5	4	1	21
- Lithium Loop	5	5			3			5	18
- Integrated Ground Assembly Test				5		4	3	5	17
- Ex-Pile Testing & Characterization Lab	1	2		2		4	3	1	13
- Liquid Metal Testing Laboratory	3	5			2			3	13
- Gamma & Neutron Irradiation	3			2	3			4	12
- Instrumented Irrad Test Loop for One FE	5				3		4		12
- Transient Reactor		2		4			2	2	10
- Hot Cells		1		3			3	2	9
- Potessium Boiling/Condensing Laboratory		5						3	8
- Nuclear-MHD Generator Facility				3				5	8
- Irradiation Capsules	3			1			3		7
- Hot Gas Testing Lab				1		3		2	6
- Single Element Test Reactor				2	3			1	6
- Nuclear Furnace				2	3			1	6
- Hot Hydrogen Testing Laboratory						4			4
- Tribology Laboratory					2				2
- Fuel Post-Hot-Gas-Test Measurements Lab				2					2
- Critical Assembly				2					2
- Cold Flow									0
- Nozzle Facility									0
									221
TOTAL	29	33	5	36	24	28	29	37	221
									1600
GRAND TOTAL	200	200	200	200	200	200	200	200	1600

Table D-8 NTP Concepts - Ranked by Main Issue

CONCEPTS

Category	Carbide					N	Oxide		Vapor	
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
▪ Performance Issues										
- Mid Band Corrosion/Cracking	4	4	5	5	5	3	3	2	5	36
- H2 Compatibility	4	1	2	4	4		4	5	5	29
- Coating Integrity & Stability	1	4	5	4	2	2	2	5	3	28
- Thermal Stress Resistance	1	1	5	3	4	3	3	4	3	27
- Fission Product Release	2	3	3	4	3	2	5	3	1	26
- Component Compatibility	3	4	5	5	2	3		2	2	26
- Element/Element Interactions	4	3	5		3	1	4	3	2	25
- High Temperature Vaporization	3	3	1	4	3	2	5	3	1	25
- Melting Point	2	3	5	3	2	1	1	4	1	22
- Composition Stability	1	1	4	4	3		4	3	1	21
- Irradiation Induced Phenomena	1	3	1	4	2	1	4	4	1	21
- UN Swelling to 10 at % Burnup		3	1	5	2	1	5	2		19
- UN Fission Gas Release to 10 at % Burnup	3			3	5	1	2	3	2	19
- Cladding/UN/Fission Product Interactions	3	1	2	3		2	4	2	1	18
- UN/Cladding Compatibility for 10 years		3	5	3	2	4			1	18
- Transient & Off-Normal Performance	1	2	3	2				5	5	18
- Fuel Pin Integrity During Launch	2		2	3	3	2	3		1	16
- UO2 Swelling at 2400K		3	5	3		2			2	15
- Emitter Creep Distortion	1	1	2	3	5	2			1	15
- Fission Product Interactions	1	1		3	3	2	3		1	14
- UO2/Tungsten Compatibility for 10 years	1	1	2	3	2	1	2		1	13
- Insulator Performance for 10 years	3	1		1	3	2		2		12
- Burnup		1		2	3	1	4		1	12
- Fission Product Migration		1			3		1	5	1	11
- Component Mech & Chem Compatibility		1			3	2	4		1	11
- Cycling Capability	4	1	1			1			1	8
- Power/Cooling Matching	3		5							8
- Fuel Element Integrity		1				1		5		7
- Neutronics & Control					4			3		7
- Turbine Bearings in Inert Atmosphere, CO2	3		4							7
- High-Temperature Thermometry	2		4							6
- Start-Up Neutron Detector	5	1								6
- Hyperconducting Generators			5							5
- Superconducting Generators	2	3								5
- High-Temperature Heat Pipes				5						5
- Radiation Shielding							4			4
- Moderator					3				1	4

Table D-8 NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Carbide					N	Oxide		Vapor	
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• Performance Issues (con't)										
- Liquid Metal Compatibility	2				2					4
- Rad-Hard High-Temp Electronics						2				2
- Shielding Materials					2					2
- Rad-Hard Themometry					2					2
- Lithium Thaw	1	1								2
- Light-Weight, High-Temp Heat Pipes		2								2
- Thermoelectric Pump Materials						1				1
- Refractory Metal Technology for Turbo-Mach										0
- Fuel Element Fabricability										0
- Insulator Performance in H2 >3000K										0
- Fuel Constituent Mass Loss vs. Time & Temp										0
- Fuel Dimension/Geometry Design Opt.										0
- Potassium Turbine										0
- Cermet Fuel Thermal Testing										0
- Nozzle Specific Impulse										0
- Alternate Nozzle Designs										0
- High Temp Pref. Carbides										0
- Hydrogen Atom Recombination										0
- MHD Channel/Electrodes										0
- Carbide Fuels										0
										584
TOTAL	63	58	82	79	80	45	67	65	45	584

Table D-8 NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

	Carbide					N	Oxide		Vapor	
Category	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **Fabrication Issues**										
- Coating Technologies	2	2	2	4	5		4	5	5	29
- QA & QC		3	5	3		3		5	5	24
- Carbon-Carbon Composites, Refractory	3	1	2	3	3			5	5	22
- Extrusion & Firing or Hot Pressing	3	3	5		3		3		3	20
- Thermocouple Alloy Development	1	1	5	1	5	1	3	3		20
- Recapture Rover/NERVA Technology	4	1	5		4		3		1	18
- Qualify Integrated Fabrication Process		1	5			4	5		2	17
- Sphere Fabrication	1	2		4	5		3			15
- Joining Refractory Metals	1	2			2	3	5		2	15
- Forming & Sintering		3				4		4	4	15
- Refractory Metal Forms & Coatings		2			3	3	2		5	15
- High CTE Graphite	4			3	5				2	14
- Pilot Plant Capability	3					4	5		1	13
- Hot & Cold Frit Development		4		5	3					12
- Carbide Fuels	5	2		5						12
- Demonstrate Bonding Plant Capability						1	4	4	1	10
- Develop Sealed Rhenium or W-25Re Clad						5	5			10
- Moderator Design & Process Development		1	2			1		5	1	10
- Neutron Detector Material Development	1				3	2	3		1	10
- Phase Distribution	2	2		3		2				9
- Homogeneous, Solid Solution	2	2	3			2				9
- Characterization	2	2				2			3	9
- Reactor Control Algorithm		2				1		5	1	9
- Automate Process		1				5	1		1	8
- Sphere Fabrication Optimization		2		3	3					8
- Design Flexibility		1	5			1			1	8
- Recapture Cermet Fuel Technology						2	5			7
- Seals		1						3	3	7
- Sheath Insulators			3					3		6
- Develop W/HfC Fabrication		1							4	5
- Carbothermic Reduction & Sintering		3							2	5
- Develop New Process								5		5
- UN Stoichiometry						3				3
- Develop High-Temp, Low Swelling Fuel						3				3
- Fiber Reinforced Carbide Fuel		1								1
- Low-Weight, High-Temp Radiators									1	1
- Particle Bed Algorithm		1								1

Table D-8 NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Carbide					N	Oxide		Vapor	
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **Fabrication Issues (cont.)**										
- High-Curie Temp Magnetic Materials (NEP)										0
- Hyper-Conducting Materials Develop (NEP)										0
- High-Temperature Emitters										0
- Integral Resevoirs										0
- Sel/Demo of W25Re Cermet Fab Process										0
										405
TOTAL	34	47	42	34	44	52	51	47	54	405

Table D-8 NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Carbide					N	Oxide		Vapor	
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **Ex-Reactor Tests**										
- Hot Hydrogen Testing	4	4	5	4	4	4	4	3	4	36
- Property Measurement	5	4	2	3	5	2	5	5	3	34
- Thermal Stress Testing	3	2	5	3	4	2	4	3	2	28
- Launch Vibration Tests	3	2		4	4	1	3	3	5	25
- Transient Testing	4	4	4		3	2	4	2		23
- Component Mech & Chem Interaction Tests	4	2		2		5	4	2	3	22
- Element Interaction Tests	3	1	3	3		2	3		5	20
- Characterization	3	3	3			2	4	4		19
- Moderator Stability Tests		2		3				5	4	14
- Cyclic Testing	1	3		3		2		4	1	14
- UO2 Stability at 2400 K							5			5
- Measure Insulator Properties			5							5
- Bearing Wear & Stability		1						3	1	5
- MHD Channel Performance				5						5
- Nozzle Tests	2	2								4
- Effect of Chemical Interactions on Cladding						3				3
- Measure UN/Fission Product Interactions						1			1	2
- Heat Pipe Performance Testing									2	2
- H + H — H2 Recombination		2								2
- Verify UN Stoichiometry Control						1				1
- UO2/Emitter/Fission Product Interactions									1	1
- Liquid Metal Testing									1	1
- H2 and Liquid Metal Testing									1	1
- Cermet Compression/Distortion Testing									1	1
- Breached Pin Lithium Loop Test										0
										273
TOTAL	32	32	27	30	20	27	36	34	35	273

Table D-8 NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Carbide					N	Oxide		Vapor	
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• **In-Reactor Tests**										
- Instrumented Fuel Element Tests	5	4	2	3	3	5		5	4	31
- Safety Tests (To Failure)	4	4		3	4	3		3	3	24
- Single Element Tests	4	3	2	3	3			4	2	21
- Shielding Materials Performance	2	2		2	3	2	3	4	1	19
- Prototypical Assembly Tests	1	4		3		5		3	1	17
- Statistical Tests	3	4		3		2			3	15
- Transient & Off-Normal Tests	3	1		3	3	3			2	15
- Fuel Pellet Irradiation		1			4	5	5			15
- Neutron Detector Performance	1	2		2	3	2	3		2	15
- Thermometry Performance & Calibration	1	1		3		1		2	2	10
- Particle Irradiations		1		2	5					8
- Electron, Neutron, & Gamma Irradiation	3	1				1			3	8
- Fuel chemistry/composition stability	4								4	8
- Reactor Control/Feedback Mechanism	1								5	6
- H2 Excitation by Fission Products								5		5
- Electrical Output Instrumented Tests									2	2
- Heat Pipe Testing									1	1
- Cermet Fuel Irradiation										0
- Hydrogen Atom Recombination										0
										220
TOTAL	32	28	4	27	28	29	11	26	35	220

Table D-8 NTP Concepts - Ranked by Main Issue (cont.)

CONCEPTS

Category	Carbide					N	Oxide		Vapor	
	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
• Facilities										
- Integrated Ground Assembly Test	3	4	5	3	4	5	5		5	34
- Materials Fabrication	4	3	5	3	4	2	5	3	3	32
- Hot Hydrogen Testing Laboratory	2	3	5	4	4	2		3	5	28
- Hot Gas Testing Lab	2	2	5		3	3	5	3	4	27
- Fuel Fabrication & Assembly (Cermet)		3	5		4	4	5	5		26
- Ex-Pile Testing & Characterization Lab	2	1	5		4	4	5	3	2	26
- Hot Cells	3	4	5	3		3	2	3	2	25
- Nuclear Furnace	5	2	5			5		5	2	24
- Transient Reactor	3	2		3		5		3	2	18
- Properties & Characterization Laboratory	3	1		3	5	1	4		1	18
- Single Element Test Reactor		3		3		5			3	14
- Gamma & Neutron Irradiation	2	1		2		3			2	10
- Irradiation Capsules	1	1		3		1	4			10
- Instrumented Irrad Test Loop for One FE		2				4				6
- Potessium Boiling/Condensing Laboratory			5							5
- Nozzle Facility	3	1								4
- Tribology Laboratory				3						3
- Critical Assembly	2	1								3
- Cold Flow	2	1								3
- Fuel Post-Hot-Gas-Test Measurements Lab	2									2
- Lithium Loop										0
- Liquid Metal Testing Laboratory										0
- Nuclear-MHD Generator Facility										0
										318
TOTAL	39	35	45	30	28	47	35	28	31	318
										1800
GRAND TOTAL	200	200	200	200	200	200	200	200	200	1800

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Table D-9 NEP, NTP Concepts - Summary Ranking of Main Issues

	CONCEPTS																	
	Nitride			Carbide			O	UF	Carbide					N	Oxide		Vapor	
Category	E2	E3	E4	E5	E7	E8	E9	E11	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
Performance Issues	81	67	110	60	81	80	65	53	63	58	82	79	80	45	67	65	45	1181
Fabrication Issues	28	47	40	34	37	44	48	45	34	47	42	34	44	52	51	47	54	728
Facilities	29	33	5	36	24	28	29	37	39	35	45	30	28	47	35	28	31	539
Ex-Reactor Tests	35	35	25	34	29	20	32	39	32	32	27	30	20	27	36	34	35	522
In-Reactor Tests	27	18	20	36	29	28	26	26	32	28	4	27	28	29	11	26	35	430
	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	3400
GRAND TOTAL																		3400

Table D-10 NEP Concepts - Summary Ranking of Main Issues

	CONCEPTS								
	Nitride			Carbide			O	UF	
Category	E2	E3	E4	E5	E7	E8	E9	E11	Total
Performance Issues	81	67	110	60	81	80	65	53	597
Fabrication Issues	28	47	40	34	37	44	48	45	323
Ex-Reactor Tests	35	35	25	34	29	20	32	39	249
Facilities	29	33	5	36	24	28	29	37	221
In-Reactor Tests	27	18	20	36	29	28	26	26	210
	200	200	200	200	200	200	200	200	1600
GRAND TOTAL									1600

Table D-11 NTP Concepts - Summary Ranking of Main Issues

	CONCEPTS									
	Carbide					N	Oxide		Vapor	
Category	T1	T2	T3	T4	T5	T8	T9	T10	T14	Total
Performance Issues	63	58	82	79	80	45	67	65	45	584
Fabrication Issues	34	47	42	34	44	52	51	47	54	405
Facilities	39	35	45	30	28	47	35	28	31	318
Ex-Reactor Tests	32	32	27	30	20	27	36	34	35	273
In-Reactor Tests	32	28	4	27	28	29	11	26	35	220
	200	200	200	200	200	200	200	200	200	1800
GRAND TOTAL										1800

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APPENDIX E
KINETICS CHARACTERISTICS OF FUELS

CONSEQUENCES OF INSTABILITY AND NONSTOICHIOMETRY IN HIGH TEMPERATURE NUCLEAR FUELS

Donald G. Schweitzer *

ABSTRACT

The search for high temperature nuclear fuels is based on obtaining melting point data from binary and ternary phase relationships. Arguments are presented that properties of important high temperature materials used in nuclear fuels and fuel element protective coatings have been obtained from nonequilibrium phase diagrams and that the materials themselves are thermodynamically unstable. These data are time dependent and should be used with caution.

Multicomponent solids at high temperatures have defect stabilized equilibrium structures that can exhibit large deviations from stoichiometry. The properties of these materials are consistent with the view that the compound acts as a solvent for the individual constituents whose activities are dependent on the overall composition of the solid solution and on the environment when the environment includes a gas containing one or more of the constituents in the solid.

At high temperatures, almost all stoichiometric refractory carbides and nitrides are unstable and evaporate incongruently. In closed systems, incongruently evaporating materials eventually achieve stable configurations that are inherently mass dependent and geometry dependent. These mass-dependent geometry-dependent properties include melting temperatures.

Many nonequilibrium stoichiometric compounds yield apparent melting points when heated rapidly while exhibiting incongruent vaporization hundreds of degrees below the reported melting points. Experiments show that the composition of nonstoichiometric single phase solids that are in equilibrium with the same vapor composition can differ from the nonequilibrium time dependent stoichiometric melting compositions by more than 50%.

Equilibrium compositions of nonstoichiometric nuclear fuels and fuel coatings are temperature dependent. The materials exhibit a wide range of evaporation rates at high temperatures. They undergo time dependent compositional and structural changes when subjected to temperature cycles and temperature gradients. Such changes can lead to complex reactivity differences in gas environments and the development of time varying internal stresses that are position dependent and composition dependent. Such effects limit the performance of high temperature fuels. Understanding the theoretical causes of these effects is important in their minimization. Minimization of the effects is important in reducing the degradation rates of both nuclear fuels and protective coatings.

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INTRODUCTION

Materials used as high temperature nuclear fuels and fuel coatings exhibit a class of instabilities that is related to the existence of nonstoichiometric structures with high defect content. These instabilities peculiar to high temperature result in novel degradation processes. The rates of these degradation processes can vary significantly even at elevated temperatures. Understanding the origin of the instabilities can provide means to control the degradation processes and reduce their rates. This paper addresses that objective.

Materials undergoing chemical reactions are in thermodynamically unstable configurations while they are reacting. Materials involved in nuclear reactions, on the other hand, can be in states representing a wide range of chemical stability. Nuclear fuel materials such as molten UC_2 in excess crystalline graphite are thermodynamically stable systems. Thermodynamic instability is developed during and after fuel performance because of irradiation effects and the accumulation of fission products. In many cases, particularly at high temperatures, irradiation effects and the accumulation of fission products are not critical factors in limiting the performance of nuclear systems. Degradation from high temperature chemical reactions often determines the lifetime of a nuclear reactor. In some cases these chemical reactions are accelerated because the starting materials are in unstable configurations. The materials commonly used as nuclear fuels and nuclear fuel coatings exhibit incongruent evaporation. Consequently, it can be shown that their equilibrium states depend upon mass and geometry.

Solids at finite temperatures require the existence of defects in order to achieve equilibrium. Defects lower the free energy of ordered solids by increasing various entropy terms. The minimum in free energy occurs when the temperature-entropy lowering is balanced by the increase in free energy required to form the defects. In general, the higher the temperature of the solid, the greater is the concentration of defects at equilibrium. The existence of equilibrium defects in conventional nuclear fuel materials, i.e., carbides, nitrides and oxides at high temperatures, allows very large deviations from stoichiometry in equilibrium structures.

If a multicomponent solid is put into equilibrium with a vapor containing one or more of its constituents then a wide range of nonstoichiometric equilibrium compositions is possible at a given temperature depending upon the applied vapor pressure. At equilibrium, the constituents common to the solid and gas must have the same activities in both phases so that variations in partial pressure of those constituents common to both phases cause variations in the equilibrium solid composition. The effects have been observed even at relatively low temperature in solids that are normally considered stoichiometric. For example, alkali halide crystals heated in either alkali metal or halogen vapors take up excess components and become nonstoichiometric. In these systems more than a dozen different

equilibrium defects and defect clusters have been proposed or identified. These include neutral cation vacancies, neutral anion vacancies, neutral divacancies, vacancies with negative charge, vacancies with virtual positive charge etc.

The interactions between nonstoichiometric solids and gases containing a common constituent can be important in high temperature nuclear reactor operation. Many high temperature nuclear reactor concepts use hydrogen as a heat transfer medium. If a carbide fuel or carbide fuel coating is exposed to the hydrogen, reaction will occur forming hydrocarbons such as methane or acetylene. The reaction will continue until the activity of the carbon in the gas mixture equals the activity of carbon in the solid. Nonstoichiometric carbides have carbon activities that are temperature and composition dependent. The solid compositions that can be put into equilibrium with a flowing hydrogen gas containing appropriate amounts of hydrocarbons cannot have time varying carbon activities. Therefore they must exhibit congruent evaporation in the hydrogen-hydrocarbon mixture.

Non-equilibrium structures are not easily distinguishable from equilibrium nonstoichiometric structures in high temperature phase measurements. It is generally difficult to predict from theory, the structure and composition of an equilibrium state with high defect content. Defects cause fairly complex changes in the equilibrium enthalpy and configurational and vibrational entropy of solids because lattice atoms adjacent to a particular defect have properties that differ from lattice atoms on regular sites or lattice atoms adjacent to a different defect [1]. Defect stabilized solids can exhibit a single phase range of nonstoichiometric compositions depending upon vapor environment, defect type and defect concentration. Titanium monoxide exhibits a homogeneity range at about 1300^{o}K between O/Ti=0.98 and O/Ti=1.25. The stoichiometric composition shows 15% vacancies in the Ti sublattice and 15% vacancies in the oxygen sublattice. At the O/Ti composition of 1.25 the material shows almost no oxygen vacancies and about 20% vacancies in the Ti sublattice. The observations are only in approximate agreement with equilibrium calculations of configurational and vibrational entropy changes and enthalpy changes associated with the defect types and interactions [2].

There are experimental difficulties as well as theoretical difficulties in distinguishing high temperature equilibrium structures from high temperature nonequilibrium structures. Knudsen cell-mass spectrometer measurements are generally limited to about 2500^{o}K. At temperatures above 2500^{o}K experimental tests of equilibrium are virtually nonexistent in nuclear fuel literature. Equilibrium properties of incongruently evaporating materials are related to their vapor pressures not their evaporation rates. In general, it is not possible to relate equilibrium properties to kinetic evaporation rates without assumptions that are often difficult to verify.

Although defect stabilization allows for a wide range of equilibrium composition, stoichiometric compositions often are not equilibrium compositions. In several instances common stoichiometric carbides, nitrides and oxides with reported melting points do not satisfy the classical equilibrium melting point concept of a first order phase transition where the composition of the solid, liquid and vapor are the same in an isolated system. Such solids when held hundreds of degrees below the apparent melting point decompose forming complex condensed phases.

EQUILIBRIUM MELTING AND CONGRUENT VAPORIZATION: GEOMETRY DEPENDENT EQUILIBRIA

Valid phase diagrams depict equilibrium relationships between temperature, composition and physical states. Nonequilibrium systems as well as equilibrium systems can be described by precise values of thermodynamic quantities. Supersaturated solutions have well defined solute and solvent activities. The major differences between the two are the reversibility and time independence of equilibrium systems and the irreversibility and kinetic changes in nonequilibrium systems. Since there is no theory that can describe the properties of nonstoichiometric equilibrium configurations, justification that measured phase diagrams are based on equilibrium data requires experimental confirmation. Confirmation includes tests of reversibility with increases and decreases in temperature, tests of reversibility with increasing and decreasing composition changes and evidence that the measured properties do not change with time. For the phase relationships discussed below, the evidence supports the view that the systems are not in equilibrium.

Classical equilibrium melting is a reversible first order phase transition where a solid isothermally converts to liquid of the same composition in a vapor of the same composition. The latent heat required to drive the transition is a rigorous and unambiguous measure of the entropy difference between the solid and liquid.

Only nonstoichiometric compositions with equilibrium vapors of the same composition can satisfy the equilibrium and reversibility melting point concepts of a first order phase transition where the solid, liquid and vapor compositions are the same. Solids that vaporize incongruently can violate classical equilibrium first order phase melting conditions in several ways. The condensed state can become multi-phase and the transition with temperature can become irreversible so that incipient melting and incipient freezing involve different compositions. In addition, incongruently vaporizing solids have equilibrium states that are mass dependent and geometry dependent. For such systems the melting compositions can be geometry and mass dependent.

High temperature melting point data are usually taken over time periods of minutes. Many equilibrium experiments of vapor compositions over solids

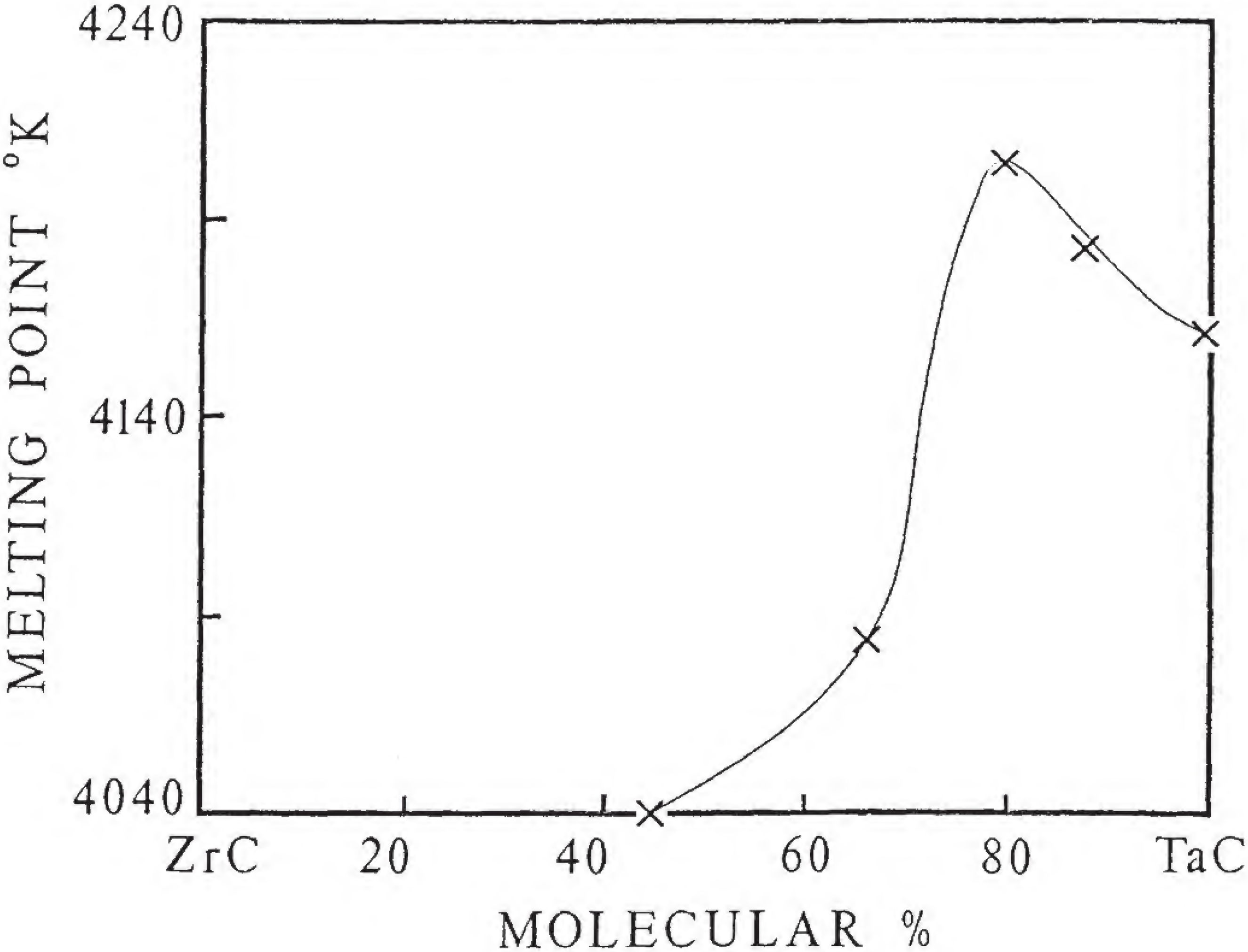

Figure E.1 Apparent Melting Points of TaC and Solid Solutions of ZrC-TaC (from ref. 7)

(Knudsen cell-mass spectrometer experiments) show that at temperatures hundreds of degrees below reported melting points, apparently stable compounds vaporize incongruently leaving nonstoichiometric and in some cases complex multi-phase solids.

A. URANIUM NITRIDE

Uranium nitride is a nuclear fuel material that has been found to decompose and become multi-phase at temperatures hundreds of degrees below an apparent short time melting point.

The melting point of uranium mononitride is given in the Handbook of Chemistry and Physics as 2900^{O}K while Lange's Handbook of Chemistry gives the value of the melting point as 2750^{O}K.

In the review article [3], "Equilibrium Studies At High Temperatures", the authors, in referring to the work of Gingerich [4], note,

"The vaporisation process of uranium mononitride was investigated in the temperature range 1919-2230K. The vaporisation occurs incongruently by preferential loss of nitrogen and the formation of two-phase system, nitrogen-saturated liquid uranium-uranium-saturated non-stoichiometric uranium mononitride. No gaseous heteronuclear species were detected."

B. TITANIUM NITRIDE

The Handbook of Chemistry and Physics lists the melting point of TiN as 3200^{O}K, while Lange's Handbook of Chemistry gives the value of the TiN melting point as 3220^{O}K.

Details of the nonstoichiometric properties of titanium nitride have been studied by several groups. In the Russian work [5], "Vaporization Rate and Thermodynamic Properties Of Titanium Nitride", the authors established that in the temperature range 1993-2260K titanium nitride has congruent vaporization compositions different from stoichiometric. They give the temperature dependence of the nitrogen to titanium ratio for congruent vaporization as

$$N/Ti = 1.46 - 2.8\times10^{-4}T \quad (1)$$

In other work [6], "The Dissociation Energy of Gaseous Titanium Mononitride", the authors state,

"After several preliminary heatings, (of $TiN_{0.98}$), chemical and X-ray analysis of the residue showed that the TiN was vaporizing incongruently and the solid was becoming richer in titanium.......

*In experiments 1 and 2 the $TiN_{0.98}$ sample was preheated in the Knudsen cell in the mass spectrometer. When the sample stoichiometry reached $TiN_{0.79}$ the ion intensity measurements were made. Analysis of the residue after each experiment showed that the stoichiometry did not change during the experiments."**

*The results from references 5 and 6 are in agreement. Experiments 1 and 2 were run in the temperature range 2279-2456K. $TiN_{0.79}$ corresponds to a temperature of 2392K from the formula given in reference 5.

C. NONSTOICHIOMETRY IN NUCLEAR FUEL CARBIDE COATINGS

Tantalum carbide, zirconium carbide and niobium carbide are all used as protective coatings for high temperature nuclear fuels, and all exhibit important nonstoichiometric properties.

Data exist for tantalum carbide confirming that some of the phase diagram values used to determine melting temperatures are inconsistent with equilibrium concepts and are time dependent values.

In [7] "High Temperature Reactions in the Systems Tantalum Carbide-Titanium Nitride-Tungsten, Tantalum Carbide-Zirconium Nitride-Tungsten and Tantalum Carbide-Hafnium Nitride-Tungsten", data taken over short time periods used to describe several phase diagrams show that tantalum carbide has an apparent melting point of about 3850^{o}C. (See, for example, Fig. 1 taken from reference 7). In the text the author describes a longer experiment in which it is stated that

"Experience has shown that the tantalum carbide is an unsuitable support media for tungsten, as it loses carbon, becoming non-stoichiometric, and melting occurs at 2710^{o}C with the formation of the W_2C-W eutectic."

Lyon [8] has shown that the congruent composition of tantalum carbide is below $TaC_{0.5}$.

The evaporation rate of carbon from compositions near $TaC_{1.0}$ has been studied by several groups [9,10,11]. Results show that the TaC composition changes significantly during the rate measurements and that the composition gradients increase as the temperature increases.

Zirconium carbide exhibits nonstoichiometric compositions between $ZrC_{0.55}$ and $ZrC_{0.98}$ [12]. Farr [13] and Sara [14] found that the congruent composition near 3000^{o}C lies between $ZrC_{0.82}$ and $ZrC_{0.87}$.

In contrast to TaC, where evaporation rates depend upon composition, the data for ZrC indicate that the evaporation rates of $ZrC_{0.67}$ [15] are not significantly different from the evaporation rates for other compositions.

NbC is one of the class of defect carbides compounds, which exhibits a wide range of homogeniety through the creation of lattice vacancies. Vacancies in the carbon sublattice occur in a face centered-cubic compound which exists between $NbC_{0.7}$ and $NbC_{0.99}$ at room temperature [16].

The temperature dependence of the composition for congruent vaporization determined in reference 16 is in good agreement with the work of Fries [17] and is shown in Fig.2. Examples of the carbon activity in the nonstoichiometric compositions at two temperatures are shown in Fig.3 taken from reference 16. At 3090^{o}C $NbC_{0.52}$ decomposes peritectically to form $NbC_{0.56}$ plus liquid [18].

It is worth noting again that much of the existing literature deals with the properties of congruently evaporating materials. For the reasons discussed below, the view taken in this paper is that important equilibrium properties in nonstoichiometric systems are determined by relationships between the condensed phases and their vapor pressures rather than between condensed phases and their evaporation rates.

D. GEOMETRY AND MASS DEPENDENT EQUILIBRIA

All solutions of volatile components, whether ideal or not, boil or evaporate incongruently unless the starting composition is azeotropic or congruent. Azeotropic or congruently evaporating solutions are the only solutions where the closed system equilibrium compositions of both the condensed phase and the vapor phase do not depend upon the volume of the system and the amount of starting material.

When multicomponent condensed phases evaporate incongruently, the more volatile component accumulates in the vapor phase in greater amounts than its original composition in the condensed phase. This requires changes in composition in the condensed phase. For ideal solutions in closed volumes, the process will continue until the activity of the individual component is the same in both phases i.e., until the vapor composition corresponds to one in which the partial pressures of the individual components are equal to the products of their pure vapor pressures and the final mole fractions in the condensed phase. At a given temperature, the final equilibrium compositions of both the condensed and vapor phases are determined by the amount of starting material and the volume into which it can evaporate. For a fixed amount of material, different equilibrium compositions will occur in different volumes. In a fixed volume, different equilibrium compositions of both the vapor and the condensed state will occur with different amounts of material originally placed in the volume.

Similar mass-geometry dependent equilibria occur for incongruently evaporating non-ideal solutions. The essential difference between ideal and non-ideal solutions

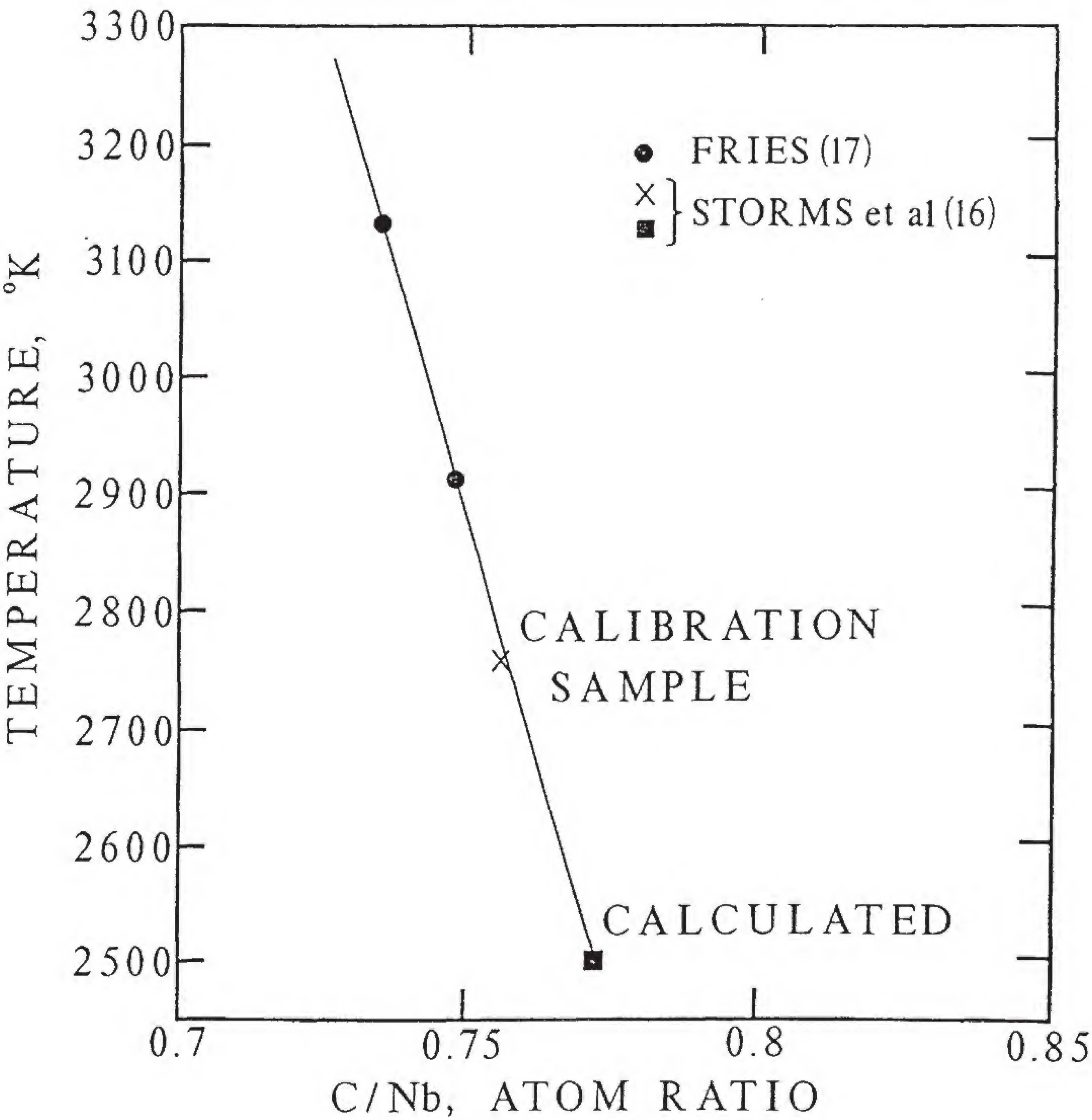

Figure E.2 Temperature Dependence of Congruent Evaporation Compositions of NbC (from ref. 16)

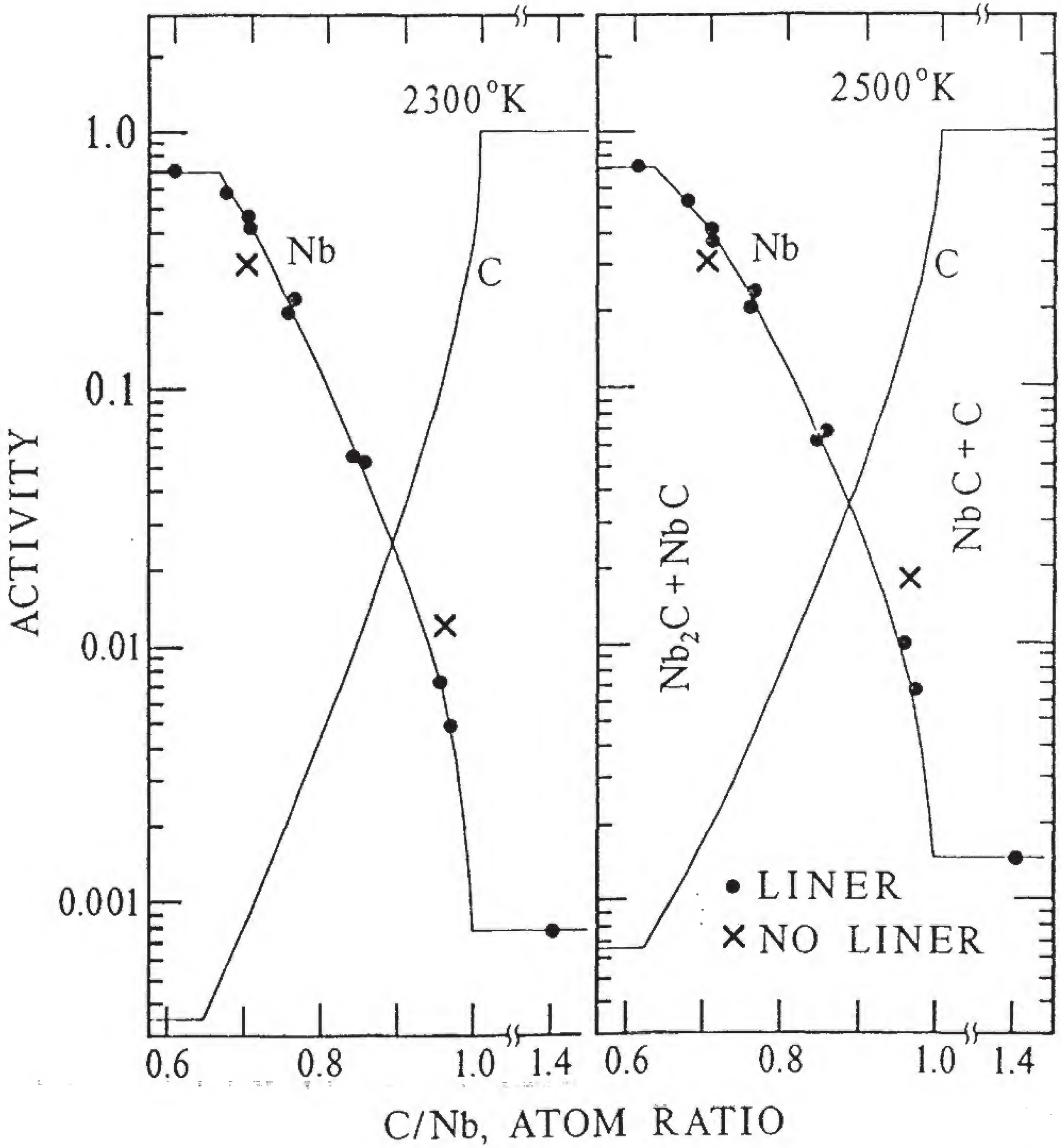

Figure E.3 Activities of Carbon and Niobium in Nonstoichiometric NbC (from ref. 16)

is due to component interactions which result in changes in the law governing the relationship between component partial pressure and the solution composition. Equilibrium configurations of non-ideal solutions are not readily calculable. In non-ideal solutions the equilibrium partial pressure of an individual component is not equal to the product of the mole fraction of the component in the condensed phase and the vapor pressure of the pure material at the given temperature.

The freezing points of solutions are composition dependent. In incongruently evaporating systems where the final equilibrium compositions are dependent upon mass and volume, the freezing point compositions will be dependent upon mass and volume.

REACTIONS AND LIMITED STABILITY OF SOLUTIONS OF NONSTOICHIOMETRIC MATERIALS

SOLUBILITIES AND REACTIONS

By definition, materials that are soluble in each other will react with each other. There is no first principle theory or empirical rule that can predict solubility ranges of ternary nonstoichiometric materials. Existing data and empirical rules deal almost exclusively with mutual solubilities of binary materials. Little is known about mutual solubilities of ternary materials with other ternaries or ternary materials with binaries.

It has been known for some time that complete mutual solubility of binary materials occurs in the cubic carbide-nitride systems when the difference in atomic radii of the metals does not exceed 15% (See for instance [7]). There is, for example, complete miscibility between UN and PuN phases, and the compounds UN and PuN are completely miscible with the corresponding uranium and plutonium carbides [19].

Knowledge of solubility ranges is important in evaluating fuel and fuel coating properties. The miscibility ranges determine available fuel compositions as well as the free energy driving force for potential fuel-coating interactions. Coating-coating reactions can occur when fuel coatings contact different coatings of adjacent reactor components. The miscibility range of coating materials is a measure of one of the theoretical driving forces for these reactions.

COMPOSITION AND TEMPERATURE RESTRICTIONS ON STABILITY

At high temperatures, each stable congruently evaporating nonstoichiometric single carbide is associated with a specific carbon activity that is temperature dependent. The same is true for stable systems composed of multiple carbides.

The changes in carbon activity with temperature are associated with changes in composition of the fuel which alter the properties and the performance of the fuel.

At low temperatures, a given solid composition can be stable over wide ranges in temperature. The compositions of nonstoichiometric solids are stable only over narrow temperature intervals. Solid solutions represented by phase boundaries change composition with changes in temperature. Single phase undersaturated solutions, [i.e., compositions displaced from the boundaries] are stable to some level of temperature change only when the vapor pressure changes with temperature do not significantly alter the solid composition (i.e., when the vapor composition is either congruent or that of a component in large excess). This condition does not apply to nonstoichiometric solids. Temperature changes cause compositional changes in both incongruently and congruently vaporizing nonstoichiometric materials. (See for example Eq. (1) and Fig. 2).

The association of desirable fuel properties with the empirical restriction of a single phase with controlled carbon activity has been recognized for several decades in engineering nuclear fuel development work. In studies on the synthesis of a (UZr)-C fuel [20], the author states,

"($U_{0.3}Zr_{0.7}$)-C has a potential operating temperature which will exceed that of unalloyed U-C by about 1000^{o}C. Accordingly (UZr)-C which is slightly hypostoichiometric in carbon may prove to be of increasing interest in ultra-high temperature gas cooled reactors, in liquid metal-bonded or liquid metal cooled reactors, and in the cesium thermionic diode.

To utilize the unique properties of (UZr)-C, a synthesis process must provide a mixed carbide which is:

(a) Single phase, (b) Dense, (c) Low in oxygen and other interstitial impurities, (d) Free from elemental carbon, (e) Free from trace impurities, (f) Uniform in U, Zr, and carbon content."

FUEL-INTERFACE INSTABILITIES

To remain stable, a single phase fuel with fixed composition and reduced carbon activity cannot be coated with another carbide whose carbon activity differs from that of the fuel, nor can it be coated with any allotropic form of pure carbon. High temperature gas cooled nuclear reactor fuels such as HTGR and NERVA fuels require, and have been developed with, coatings of buffer carbon, pyrolytic carbon (PC), and various carbides including ZrC and NbC. In general, none of these coatings can be in equilibrium with the fuel.

The fuels and the fuel coatings are also unstable at high temperatures in both inert and hydrogen environments for several other reasons. At high temperatures, nonstoichiometric U-C fuels will react and migrate through the carbon coatings to form UC_2, the only composition stable in an environment buffered with unit carbon activity. The ZrC and NbC coating compositions that are stable to excess carbon are not the congruently evaporating compositions so that one side of the coating will degrade and change composition (and properties) with time. This would be true even if the coolant side of the coating had an original composition that was stable to the gas at the selected temperature. The diffusion of the higher activity carbon from the inside of the coating to the outside will increase the original value of the coolant side carbon activity. On the gas side of the coating, some or all of the excess carbon will be removed by either evaporation or reaction with hydrogen. In time, a carbon activity gradient and a carbide compositional gradient will be established through the coating thickness with concomitant continuous removal of carbon from the excess carbon under the coating. This will occur even if the coating maintains integrity with respect to surface coverage. If stresses develop and the coating cracks or flakes, the degradation rates will be even greater.

Degradation rates can be large with small temperature gradients. Some degradation can also occur rapidly under isothermal conditions. For example, carbides that are stable in the presence of excess graphite will preferentially dissolve disordered carbon and precipitate graphite [21,22,23]. The reaction is driven isothermally by the excess free energy of the disordered carbons. Fitzer and Kegel [22] studied the behavior of carbon saturated molten vanadium carbide, as well as nickel, zirconium and iron. These melts did not react with natural flake graphite but penetrated PC at a moderate rate and glassy carbon very rapidly. All the samples were pretreated for 1 hour at 3000^{o}C. The results indicate that even at these temperatures the graphitization kinetics are not rapid enough to allow the conversion of disordered carbons or PC to low free energy graphite. Gillot et al.[23] showed that the phenomena can also occur in the solid state at elevated temperatures. Some of these effects have been confirmed in observations related to reactor operation. Migration of oxide and oxycarbide fuels and attack of fuel coatings was a frequently observed degradation mechanism in early HTGR studies. In studies on the failure mechanisms of HTGR fuels at temperatures where graphite sublimation rates are appreciable (3300^{o}C), it was found that molten UC_2 was retained in low free energy nuclear grade graphite H451 for several hours without any significant dissolution of graphite or migration through the graphite [24,25]. Similar studies made in glassy carbon containers showed extensive attack of the glassy carbon by UC_2 after 10 minutes at 2800^{o}C.

REACTION WITH HYDROGEN

In high temperature nuclear reactor concepts that use hydrogen as a heat transfer medium, carbide fuels or fuel coatings exposed to the hydrogen will react forming hydrocarbons such as methane or acetylene. In a closed system the reaction will continue until the activity of the carbon in the gas mixture equals the activity of carbon in the solid. Nonstoichiometric carbides have reduced carbon activities that are temperature and composition dependent. In an open system, only a composition that is evaporating congruently can remain in equilibrium with a hydrogen gas containing small amounts of hydrocarbons whose carbon activity has been matched to that of the solid. The equilibrium quantities of hydrocarbons needed to match a known solid carbon activity can be obtained from past studies and from the JANAF Tables. (The JANAF Table values are listed in Table I.) Information also exists on the rates of these reactions at various temperatures.

At temperatures below $1000^{\circ}C$, the reaction rate of hydrogen with graphite is negligible and much smaller than it is with coals, charcoals, chars, coke and disordered carbons formed by decomposition of carbon monoxide and hydrocarbons. At low temperatures the reaction rate is small and at higher temperatures the equilibrium concentration of methane becomes small. Significant rates occur between $1000^{\circ}C$ and $1300^{\circ}C$ in hydrogen pressures above 10 atm.

According to Hedden [26], equilibrium concentrations of methane introduced into the hydrogen show that the reaction rate does in fact approach zero.

A. Relative Effects of Methane and Acetylene

The JANAF Tables show that the equilibrium constant for the formation of acetylene (ethyne) is

$$K_{eq}\ 3000K = PC2H2/PH2 = 6.2 \times 10^{-11} \quad (2)$$

whereas the equilibrium constant for the formation of methane is

$$K_{eq}\ 3000K = PCH4/[PH2]^{2} = 6.0 \times 10^{-5} \quad (3)$$

The values require that at $3000^{\circ}K$, the equilibrium concentrations of acetylene are less than the equilibrium concentrations of methane for all hydrogen pressures greater than about 100mm. These values are confirmed by the work of Clarke and Fox [27]. No other carbon-hydrogen species were found in significant concentrations.

DISCUSSION

All nuclear fuel compositions of binary and ternary solid solutions are thermodynamically unstable at those temperatures where the composition corresponds to an incongruently vaporizing composition. Nonstoichiometric materials confined in their congruent vapors are only stable at a single temperature or over narrow temperature ranges.

All carbide nuclear fuels will react with hydrogen unless they can be buffered by more reactive excess carbon. Although this type of protection may be possible for UC_2 which is stable in systems containing excess graphite, it is not possible for binary and ternary solid solution fuels which are stable only when they are hypostoichiometric in carbon. Such fuels change composition in excess carbon environments.

Because of instability, binary and ternary solid solution nuclear fuels have intrinsic rates of degradation. They can only be used under conditions where the type of degradation is tolerable or where the intrinsic rates of degradation are slow. If extended fuel performance is required and thermal decomposition of the fuel is slow enough to be acceptable, binary and ternary solid solution fuels must have appropriate coatings to retain fission products and to protect against coolant reactions.

SUMMARY OF GENERIC INSTABILITIES

Stability problems of coated fuel systems fall into four areas, a) reactions within the coatings , b) reactions of the coating in the coolant gas environment, c) reactions within the fuel, and d) reactions at the fuel-coating interface.

a) Internal coating reactions similar to the fuel instability reactions exist for the common high temperature niobium carbide, tantalum carbide and zirconium carbide coatings. If the composition corresponds to an incongruently vaporizing composition, the coating is unstable at all temperatures. If the coating corresponds to a congruently vaporizing composition, it is stable only over a limited temperature range in its own vapor.

b) If evaporation of the metal component can be ignored, the coating reactivity to hydrogen can be reduced in specific hydrogen-hydrocarbon mixtures where the carbon activity of the gas is matched to the carbon activity of the congruently vaporizing coating.

c) The most generic aspects of reactions within the fuel are changes in composition resulting in phase changes with concomitant property changes i.e., melting accompanied by fuel migration and changes in fission product retention.

d) In general, the carbon activities of fuel coatings will differ from the carbon activities of the fuels. At high temperatures the two can react if in contact. The reaction will change both the fuel and coating compositions with an eventual degradation in integrity and alteration in performance. If the coating contains a metal common to the fuel, such as Zr or Nb, there will be an additional activity mismatch between fuel and coating leading to a greater free energy driving force for reaction. Although the rates of such high temperature interactions may depend on the surface treatments, contact pressures, contact angles, grain sizes etc., some high temperature data for these materials indicate that there are additional defect driven degradation reactions with relatively rapid reaction times.

The reactions of TaC with ZrC and ZrN at temperatures between 2700^{o}C and 3900^{o}C were studied by LeMaistre [7]. TaC-ZrC interfaces are thermodynamically unstable at high temperatures. TaC and ZrC form completely miscible solid solutions with a maximum in apparent (short time) melting temperature above 3900^{o}C, (about 50^{o}C above the apparent melting point of TaC) at a composition of about 80% TaC (Fig.1). The materials diffuse into each other rapidly at high temperatures. Thermodynamic calculations made by LeMaistre indicate that TaC and ZrN should not react so that the driving force for interdiffusion in the TaC-ZrN system should be reduced relative to the driving force for interdiffusion in the TaC-ZrC system. However, the data for the TaC-ZrN system show extensive interaction (movement of Zr into the TaC phase) after 5 minutes at 2900^{o}C.

LeMaistre offers a mechanism for the unexpected diffusion of ZrN into TaC. Initially a limited cation exchange occurs across the ZrN-TaC interface. Diffusion of the Zr ions into the voids of the TaC occurs, creating vacancies and enabling further diffusion of the nitride ion into the tantalum carbide. It is claimed that this mechanism for cation diffusion is also applicable to anion diffusion although nitrogen and carbon cannot be detected by the electron probe analyzer used to demonstrate the movement of Zr into the TaC.

The results allow that even in the absence of conventional free energy driving forces,(i.e., free energy driving forces based on chemical composition), there are defect driven mechanisms through which metal carbide and metal nitride surfaces in contact at these temperatures may bond in short times.

CONCLUSIONS

Equilibrium states of solids at high temperatures require the existence of large concentrations of various types of defects. The defects stabilize single phases with wide ranges of nonstoichiometric compositions. Only narrow composition ranges of nonstoichiometric materials have congruent vapor pressures. The congruent compositions change with temperature.

Nuclear fuels and fuel coatings made of intrinsically nonstoichiometric materials are unstable under most conditions of operation. They decompose by evaporation during use. In many cases their apparent melting temperatures have been obtained from time-dependent, mass-dependent, volume-dependent, nonequilibrium phase relationships. The properties of such materials are temporal and generally unpredictable. The use of such materials in reactor designs is based on determining those parameters that reduce the degradation rates to acceptable levels.

Important properties of nonstoichiometric materials are geometry dependent and mass dependent. Because of this geometry and mass dependence, the absence of theory and data for the degradation processes in systems using ternary materials prevents significant extrapolation or scaling of required measurements. The properties and degradation reactions must be studied under realistic conditions. Experience from chemical kinetic studies of nonstoichiometric binary materials [28] shows that a large number of parameters are involved in pertinent property changes. These include many poorly understood structural and metallurgical variables which define macroscopic and microscopic properties. These variables require control for reproducible preparation of acceptable nuclear fuels and fuel coatings.

Temperature gradients in both the fuels and fuel coatings cause compositional instabilites that are peculiar to nonstoichiometric solids. Because of this, small sizes and small geometries can have important advantages in the successful development of nuclear fuels and coatings.

The freezing points of fuel solutions are composition dependent. In incongruently evaporating systems where the final equilibrium compositions are dependent upon mass and volume, the freezing point compositions will be dependent upon mass and the volume which encloses the vapor. If such materials are used as nuclear fuels, geometries which allow control of the fuel vapor volumes have important advantages.

Existing literature is based almost exclusively on binary materials. Virtually nothing is known about changes due to inherent instability in high defect content ternary materials. Consequently, a great deal of high temperature-high pressure work will be required to understand and reduce degradation in systems utilizing ternary materials.

TABLE I

METHANE - HYDROGEN EQUILIBRIA

[For unit carbon activity and H_2 in atm.]

T^oK	$p_{CH_4}/p^2_{H_2}$ [$K_{eq.}$]	ppmCH_4 H_2 = 1	ppmCH_4 H_2=10	ppmCH_4 H_2=100
800	1.374	578000	932000	100%
900	0.316	240000	760000	
1000	0.0959	87,500	490000	905000
1100	0.0357	34,500	263000	780000
1200	0.0156	15,400	135000	609000
1300	0.00767	7,600	71,000	434000
1400	0.00418	4,200	40,000	295000
1500	0.00246	2,500	24,000	173000
1600	0.00155	1,600	15,250	134000
1700	0.00103	1,030	10,000	91,000
1800	0.000713	710	7,000	65,000
1900	0.000514	500	5,000	47,000
2000	0.000384	380	3,800	38,000
2500	0.000126	125	1,250	12,500
3000	0.0000603	60	600	6,000
3500	0.0000357	36	360	3,600
4000	0.0000240	25	250	2,500

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13. ABSTRACT (*Maximum 200 words*)

This report was prepared by members of the Fuels, Materials and Related Technologies Panel, with assistance from a number of industry observers as well as laboratory colleagues of the panel members. It represents a consensus view of the panel members. This report has not been subjected to a thorough review by DOE, NASA or DoD, and the opinions expressed herein should not be construed to represent the official position of these organizations, individually or jointly. There are no implications of funding decisions in the strategies presented here. The authorship represents major contributors to the writing of the report. All panel members and observers (see list in Appendix A) made very substantial contributions to the contents of the report. Additional information provided by the concept focal points is also gratefully acknowledged. This report was actually written in 1991 and is consistent with the charter and direction given to the panel, based upon the approved national program at that time. However, due to changes in national space policy and planning, some of the information has become dated. The final version of the report has incorporated some of these changes. However, a total update of the report is not planned at this time.

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